Effect of clouds on aerosol properties; a view from satellite and ground-based observations

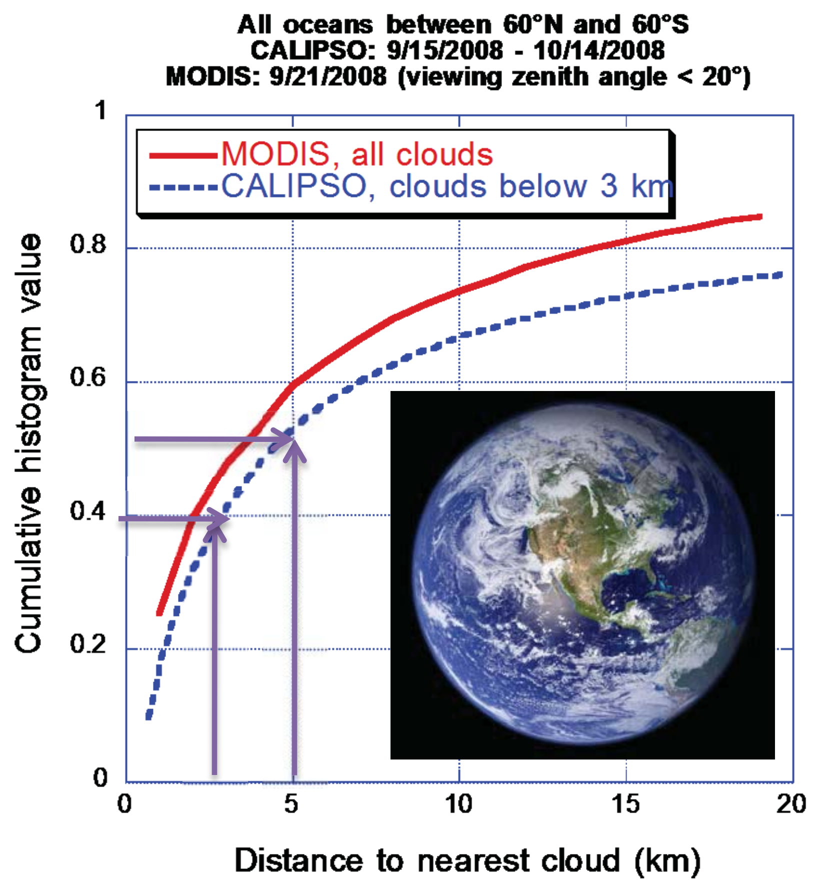
A. Marshak (NASA GSFC),
T. Varnai (JCET), W. Yang (GESTAR),
G. Wen (GESTAR), P. McBride (GESTAR)

Motivation

• Climate studies (e.g., aerosol indirect effect) demand a precise **separation of clear and cloudy** air;

• Remote sensing **retrieval** of aerosol properties near clouds is a big **challenge**;

• Excluding aerosols near clouds will dramatically reduce the database and **underestimate** the forcing, while including them may **overestimate** it because of unaccounted cloud contamination



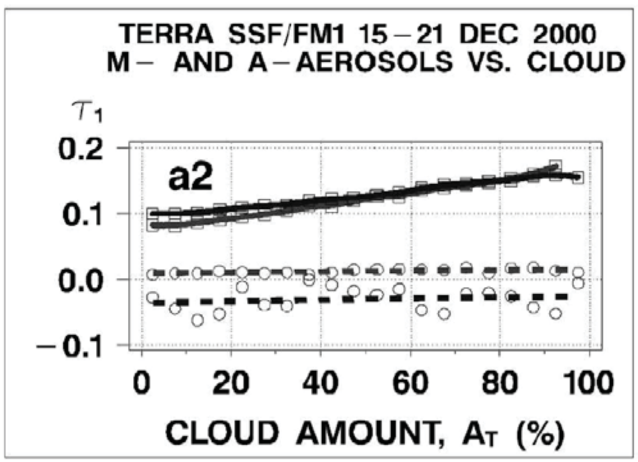
from **MODIS**: 60% of all clear sky pixels are located 5 km or less from all clouds
from **CALIPSO**: 50% of all clear sky pixels are located 5 km or less from low clouds
(e.g., Twohy et al., 2009)

What happens to aerosol in the vicinity of clouds?

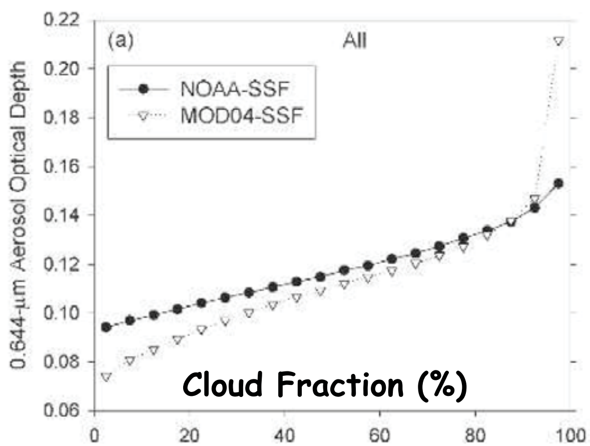
All observations show that aerosols seem to grow near clouds

or

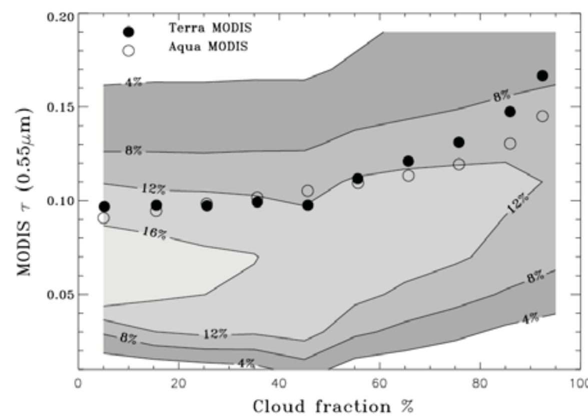
(to be safer) "most satellite observations show a positive correlation between retrieved AOT and cloud cover", e.g.:



from Ignatov et al., 2005



from Loeb and Manalo-Smith, 2005



from Zhang et al., 2005

What happens to aerosol in the vicinity of clouds?

However, it is not clear yet how much grows comes from

- “real” microphysics, e.g.
    - increased hydroscopic aerosol particles,
    - new particle production or
    - other in-cloud processes.

- “artificial” effects, e.g.
    - cloud contamination (sub-pixel clouds),
    - extra illumination from clouds (a clear pixel in the vicinity of clouds)

Both “artificial” effects may significantly overestimate AOT.

Twohy et al. (2009)

estimated that "*the aerosol direct radiative effect as derived from satellite observations of cloud-free oceans to be 35-65% larger than that inferred for large (>20 km) cloud-free ocean regions.*"

Jeong and Li (2010)

found that "aerosol humidification effects can explain about one fourth of the correlation between the cloud cover and AOT."

Chand et al. (2012)

found a 25% enhancement in AOT between CF 0.1-0.2 and CF 0.8-0.9. This "*enhancement is consistent with aerosol hygroscopic growth in the humid environment surrounding clouds.*"

Bar-Or et al. (2012)

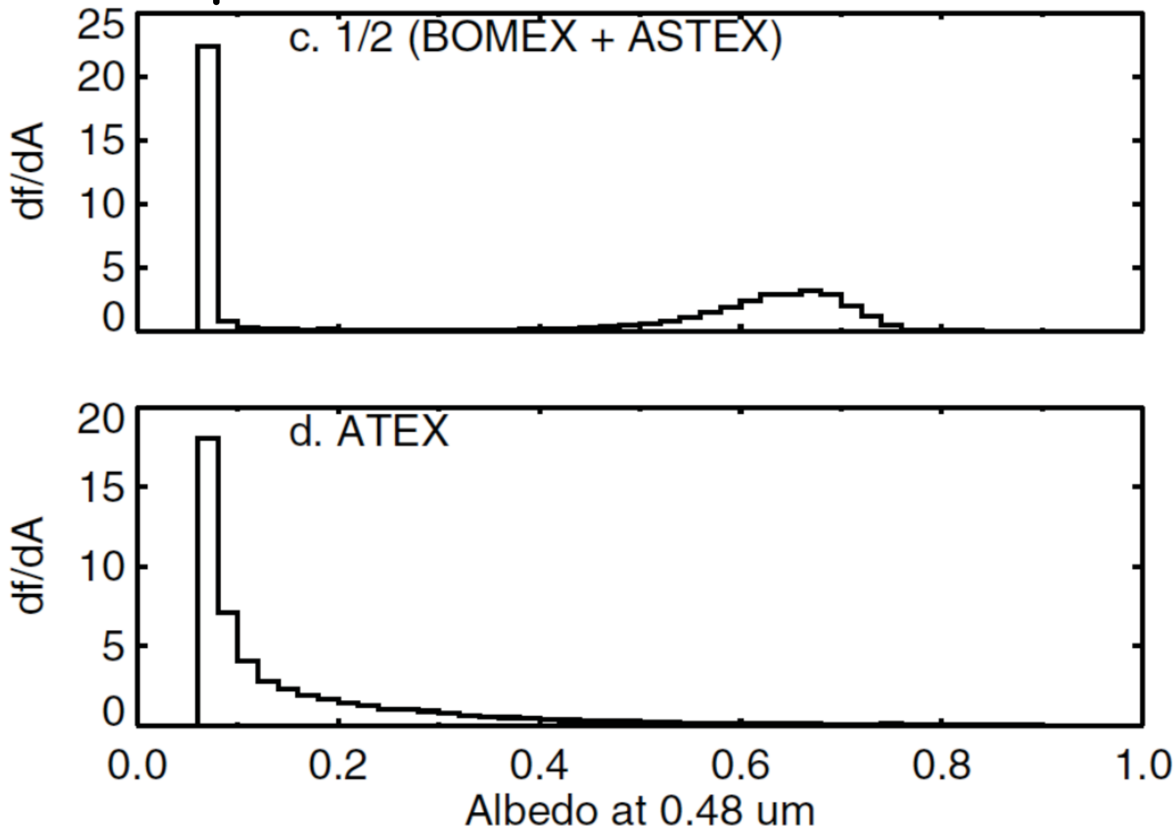
argued that "*at least for warm Cumulus cloud fields, the variations of the mean RH values are negligible at distances larger than ~0.5 km from clouds.*"

From Chapter 7 of IPCC AR5 report

*… aerosol measured in the vicinity of clouds is significantly different than it would be were the cloud field, and its proximate cause (high humidity), not present. The latter results from **humidification effects** on aerosol optical properties, **contamination by undetectable cloud fragments** and **the remote effects of radiation** scattered by cloud edges on aerosol retrieval.*

Inseparability of cloudy and clear skies under partial cloud cover (from Charlson et al., 2007)

Albedo pdfs from LES of trade Cu and Sc clouds



average of the BOMEX (~10% cloud cover) and ASTEX (overcast) fields; clear and cloudy contributions are nicely separated

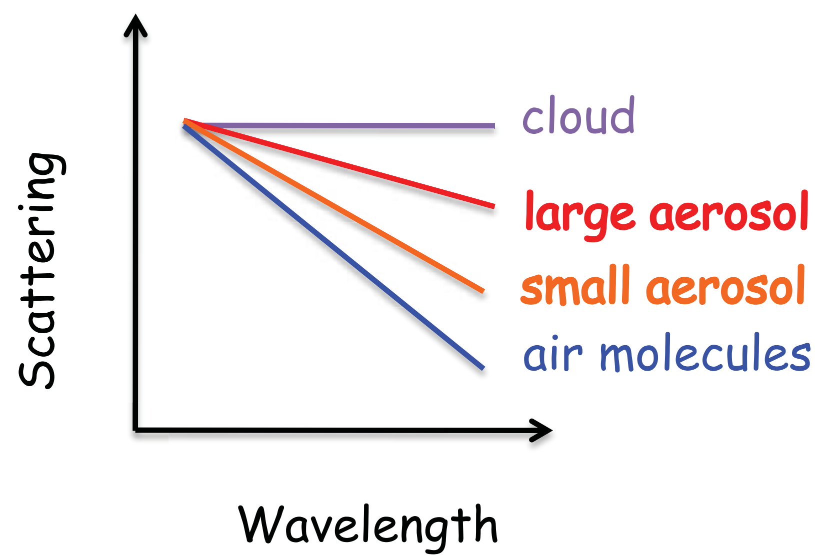
for ATEX trade Cu (~50% cloud cover), with the albedos from clear and cloudy portions inseparable

"The existence of partly cloudy regions and the fact that the clear-cloudy distinction is ambiguous and aerosol dependent raise the possibility that the conventional expression may lead to errors." (Charlson et al., 2007)

Let's check CALIPSO and MODIS observations

CALIPSO Data

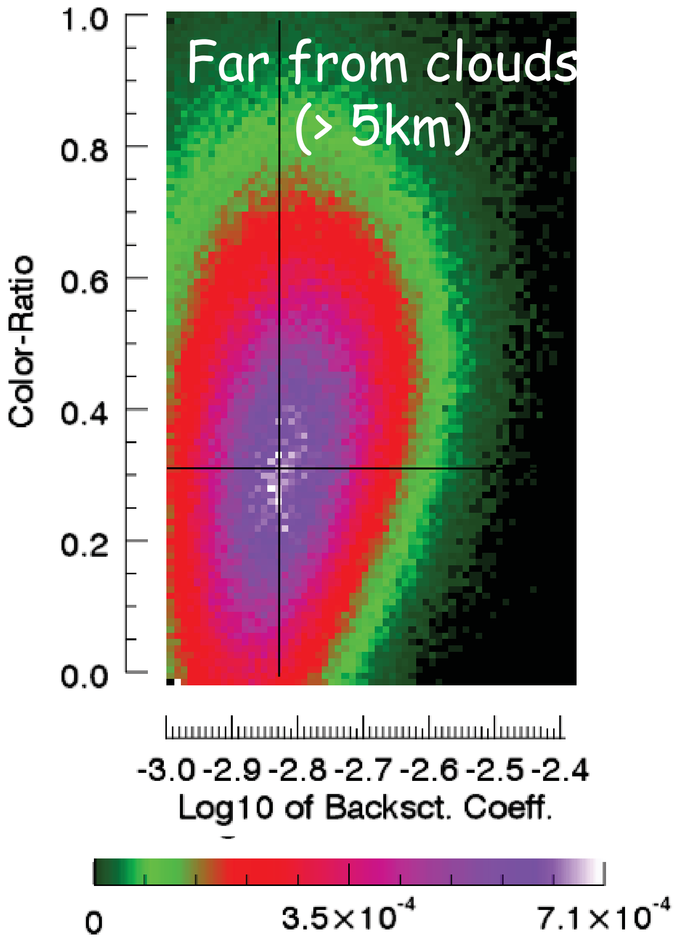
attenuated backscatter coefficient: β'
attenuated color ratio: χ',
depolarization ratio: δ'

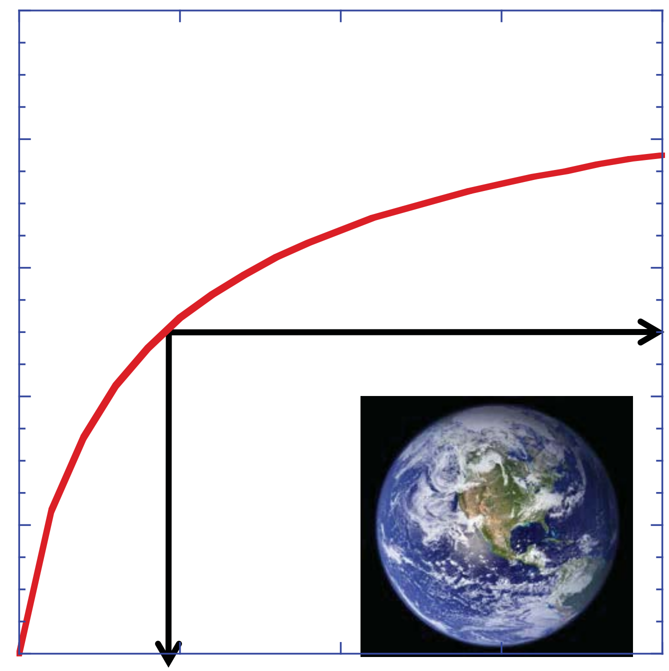


CALIPSO

(ColorRatio vs. Backsct close to and far from clouds)

Global night data over ocean



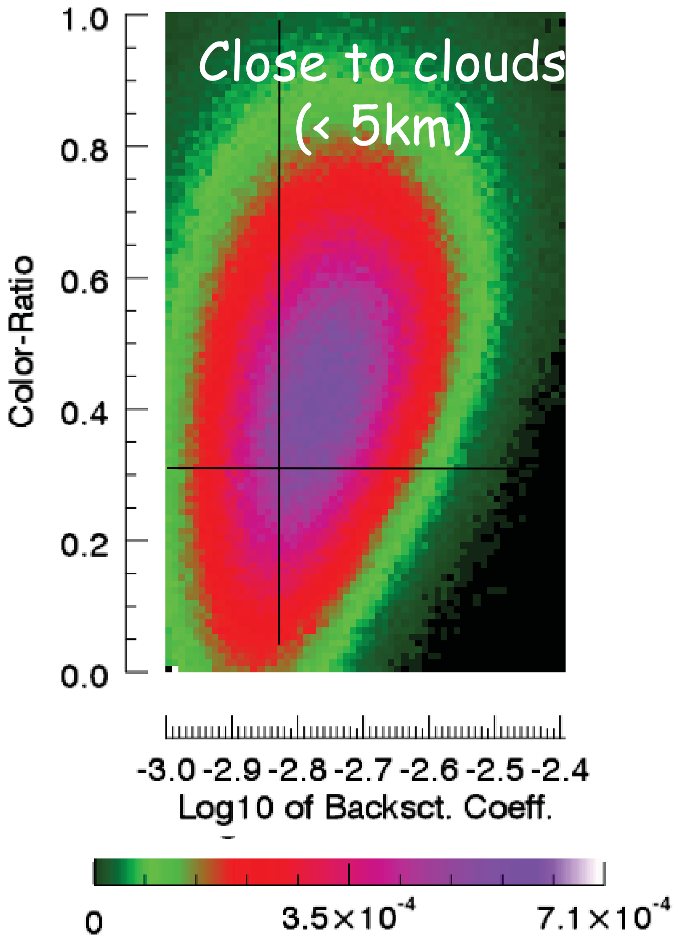


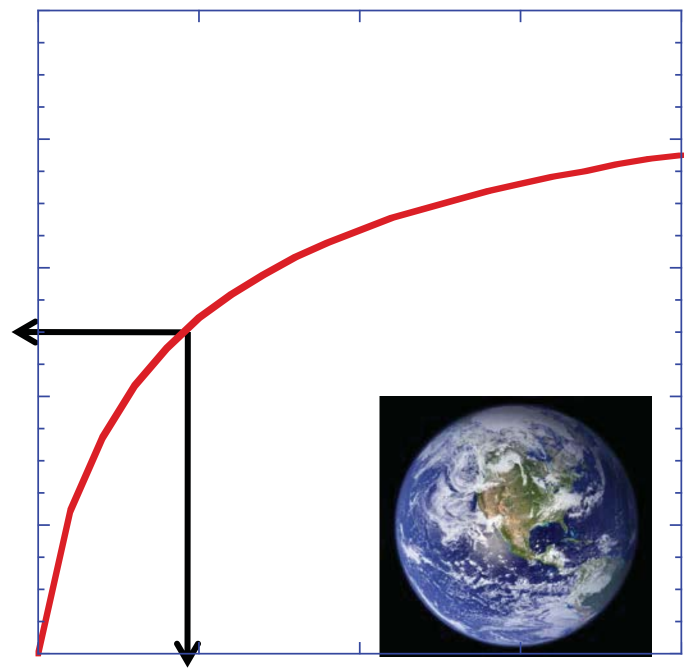
Fraction of cloud-free vertical profiles

CALIPSO

(ColorRatio vs. Backsct close to and far from clouds)

Global night data over ocean

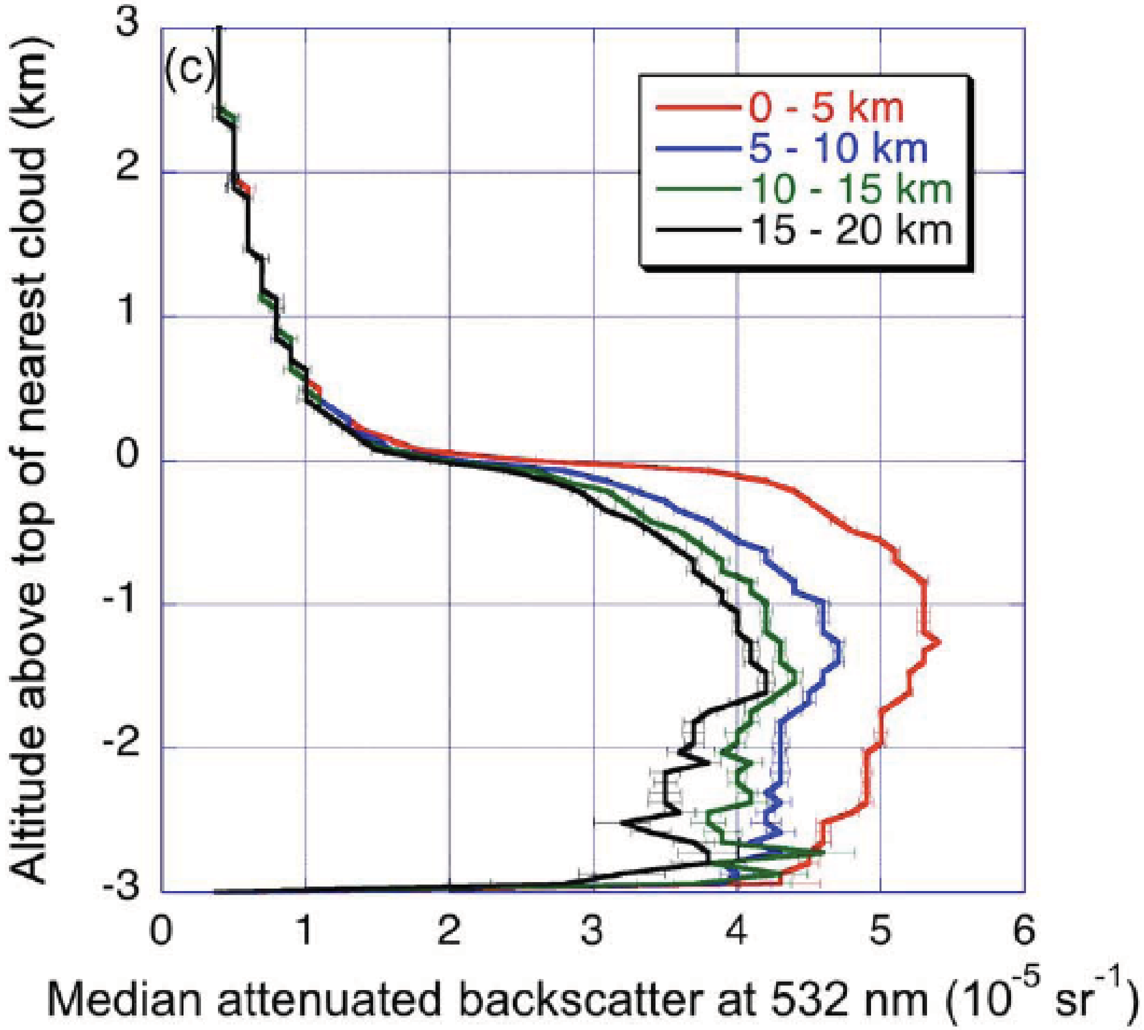


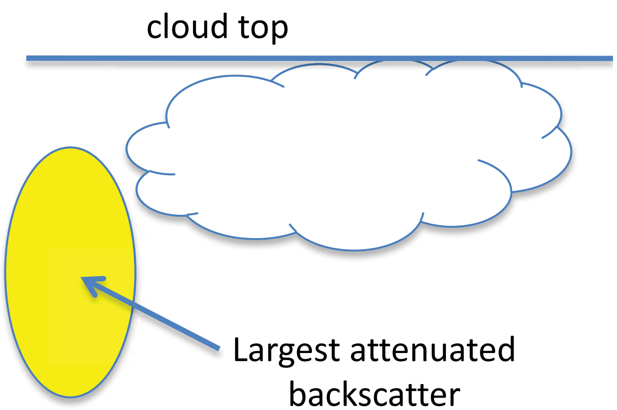


Fraction of cloud-free vertical profiles

CALIPSO

Varnai and Marshak, 2011

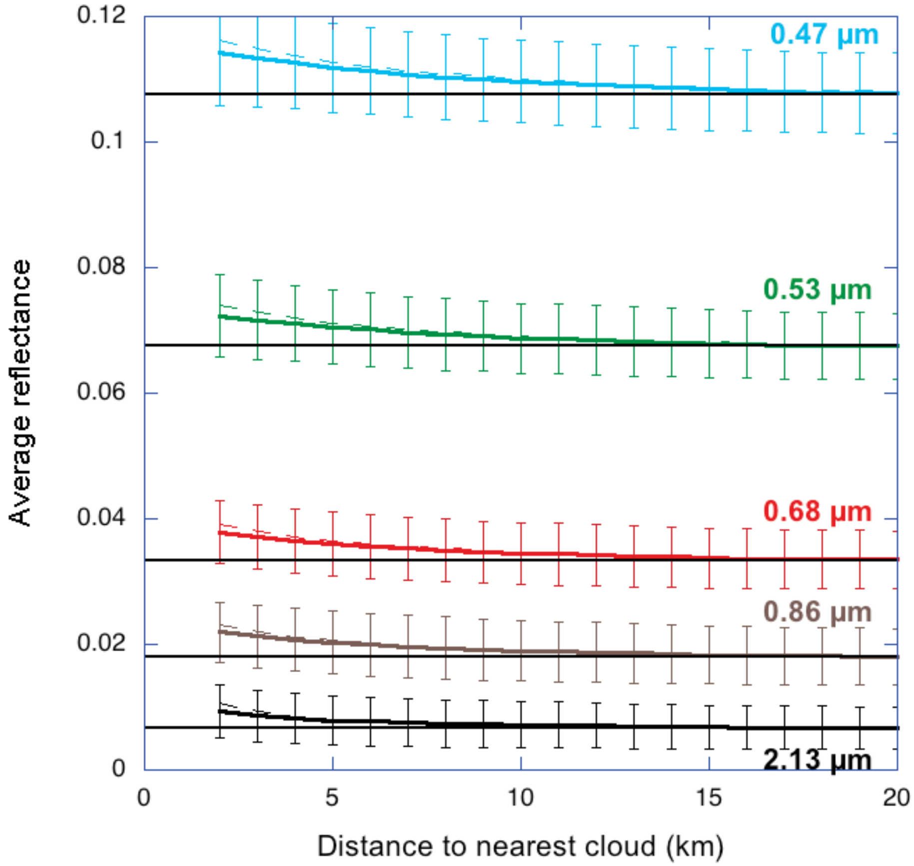




Global over ocean data for Sep-Oct 2008

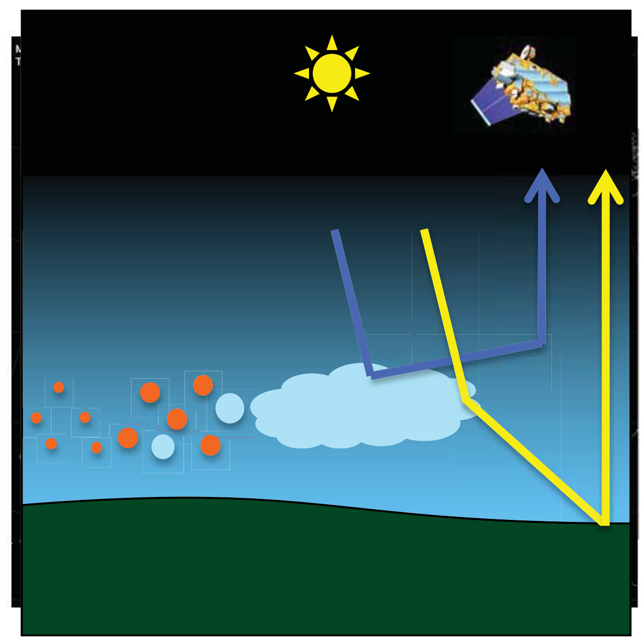
MODIS

NE Atlantic Ocean, MODIS Terra
2000-2007, September 14-29



Reflectance increase may come from:

- Aerosol changes (e.g., swelling in humid air)
- Undetected cloud particles
- Instrument imperfections
- 3D radiative effects

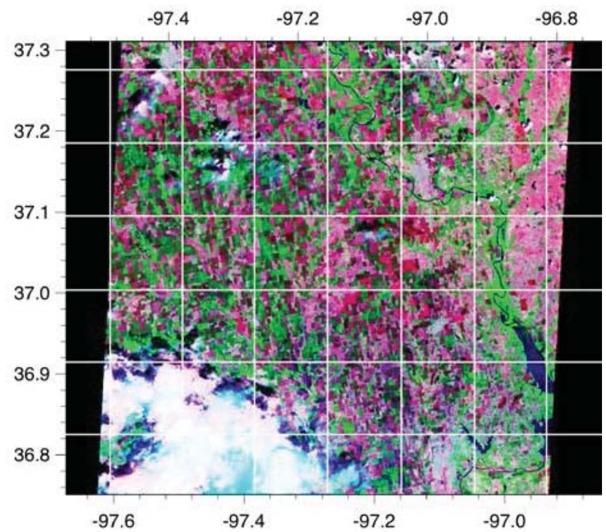


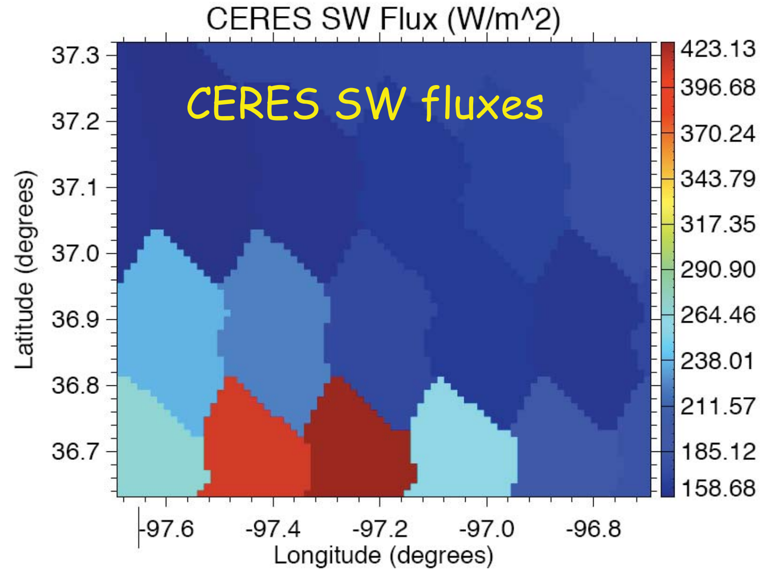
Várnai and Marshak (2009)

ASTER image over ARM SGP:20060430

ASTER image ~ 80 by 80 km

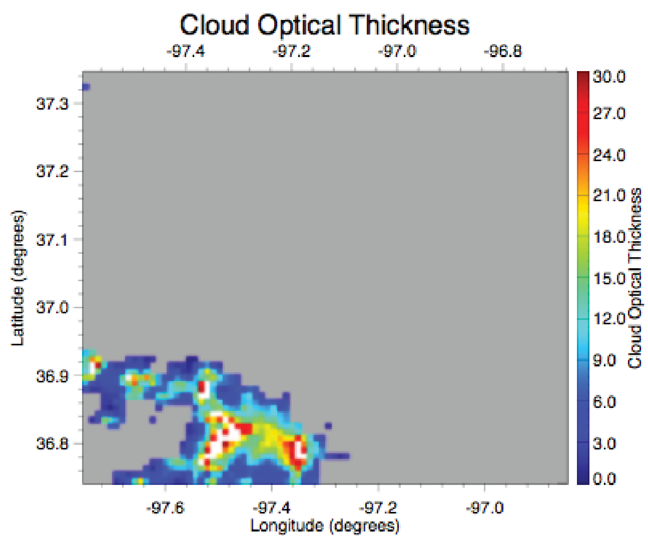
Advanced
Spaceborne
Thermal **E**mission
and **R**eflection
Radiometer



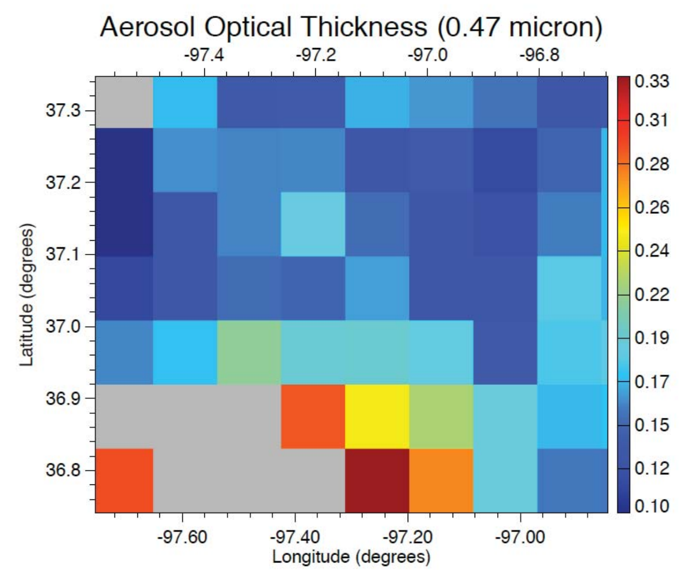


MODIS
retrievals

Cloud Optical Thickness



Aerosol Optical Thickness



Wen et al., 2007

These are Observations.
What's about Products?

AERONET data

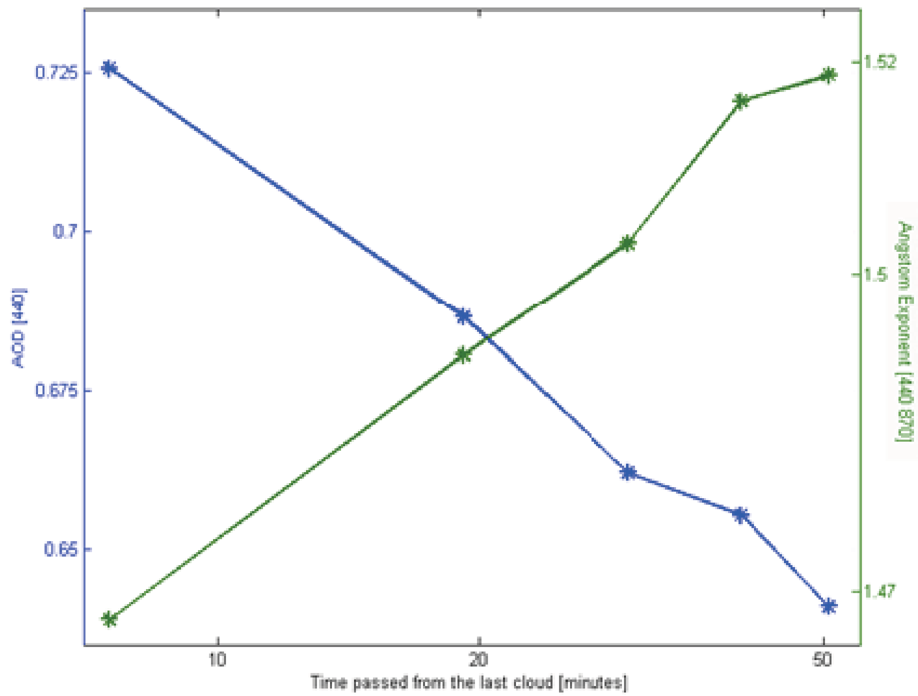
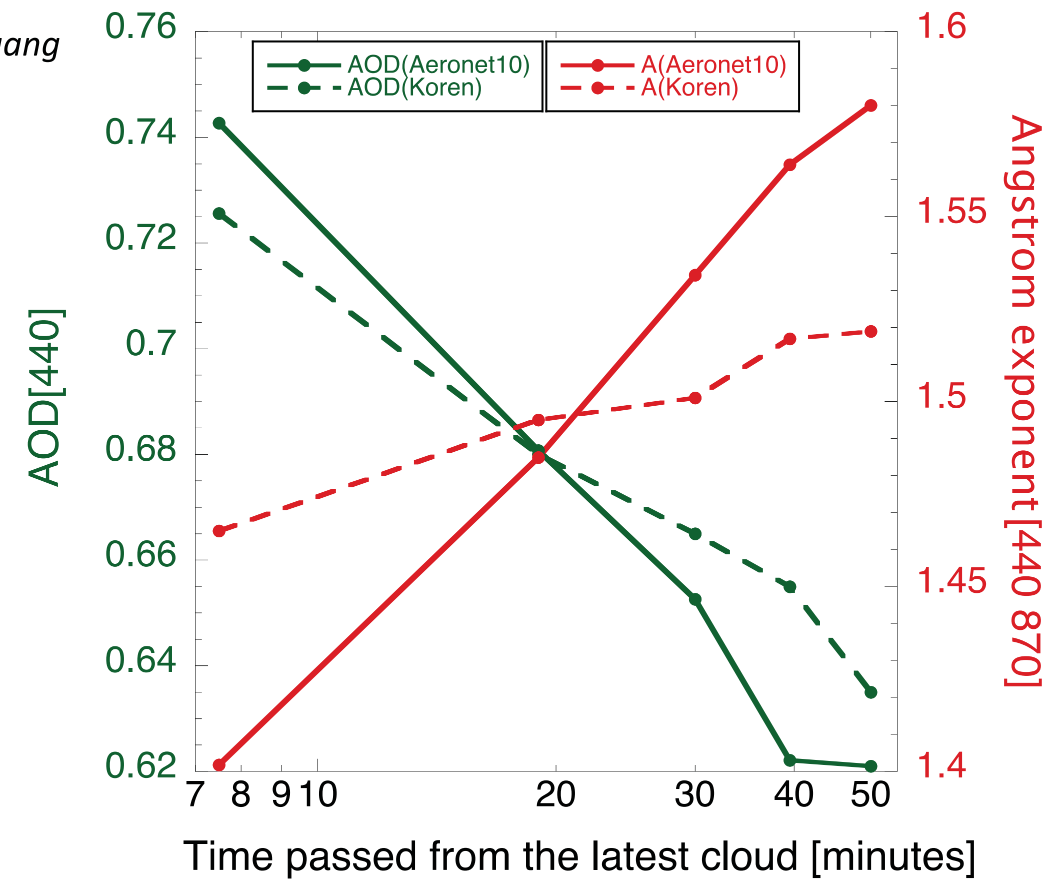


Figure 3. An analysis of AERONET data for Alta-Floresta (Brazil) during the biomass (dry) season 2000–2004, as a function of the estimated distance from the nearest cloud. Blue, AOD at 440 nm; green, Angstrom exponent (440, 870). Standard error of the averaged AOD's is 2% and of the Angstrom exponent 3% for this station.

from Koren et al., 2007

AERONET data

Courtesy of Stefani Huang



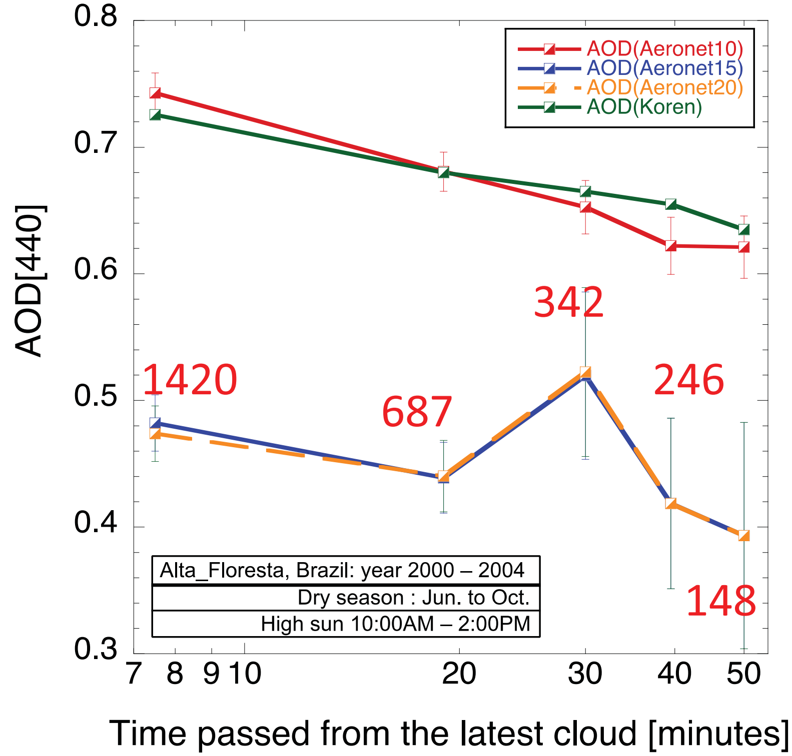
An analysis of AERONET Level 1[1] and Koren et al., (2007)[2] data for Alta-Floresta (Brazil) during the biomass burning (Jun. to Oct., 2000-2004), as a function of the distance from the nearest cloud.

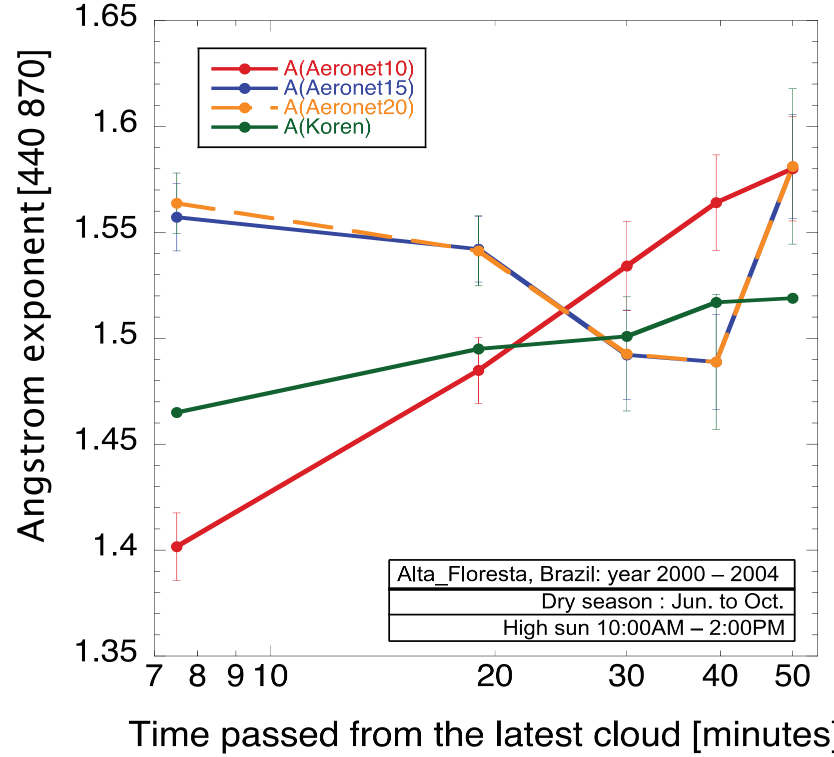
[1] Unscreened data

[2] Applying Kaufman's cloud screening

AERONET data

Courtesy of Stefani Huang

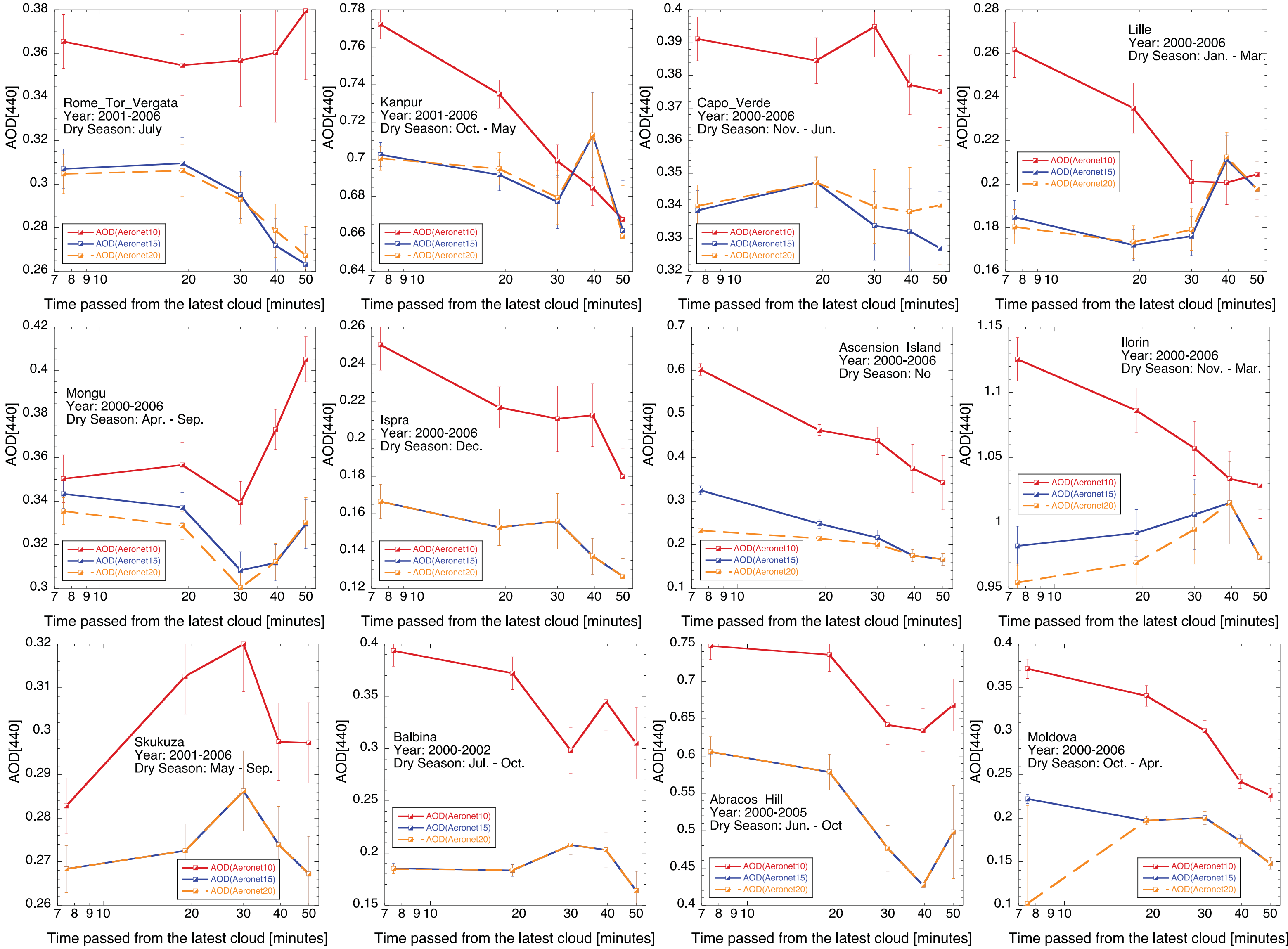




A comparison of different data set: AERONET Level1[1], Level 1.5[2], Level 2.0[3], and Koren et al., (2007)[4] data for Alta-Floresta during the biomass burning (June to Oct., 2000-2004).

[1] Unscreened data
[2] Cloud-screened data but may not have final calibration applied. These data are not quality assured.
[3] Pre- and post-field calibration applied, cloud-screened, and quality-assured data
[4] Applying Kaufman's cloud screening

12 other AERONET stations around the globe: AOD (440 nm)

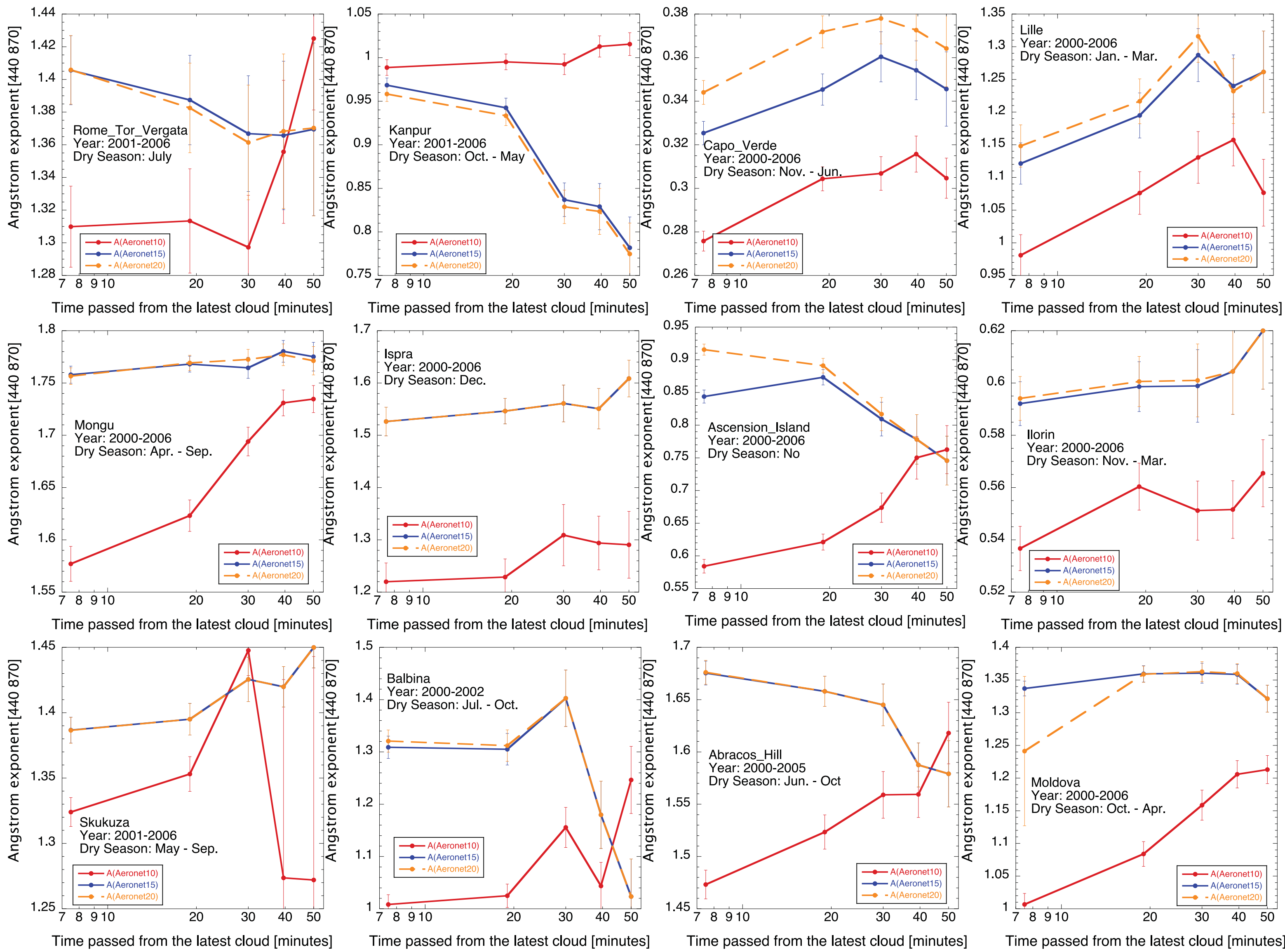


Capo_Verde
Level10: 3127, 2410, 1257,1119, 846
Level15: 2367, 1650,700, 542, 317
Level20: 2181, 1519, 658, 509, 295

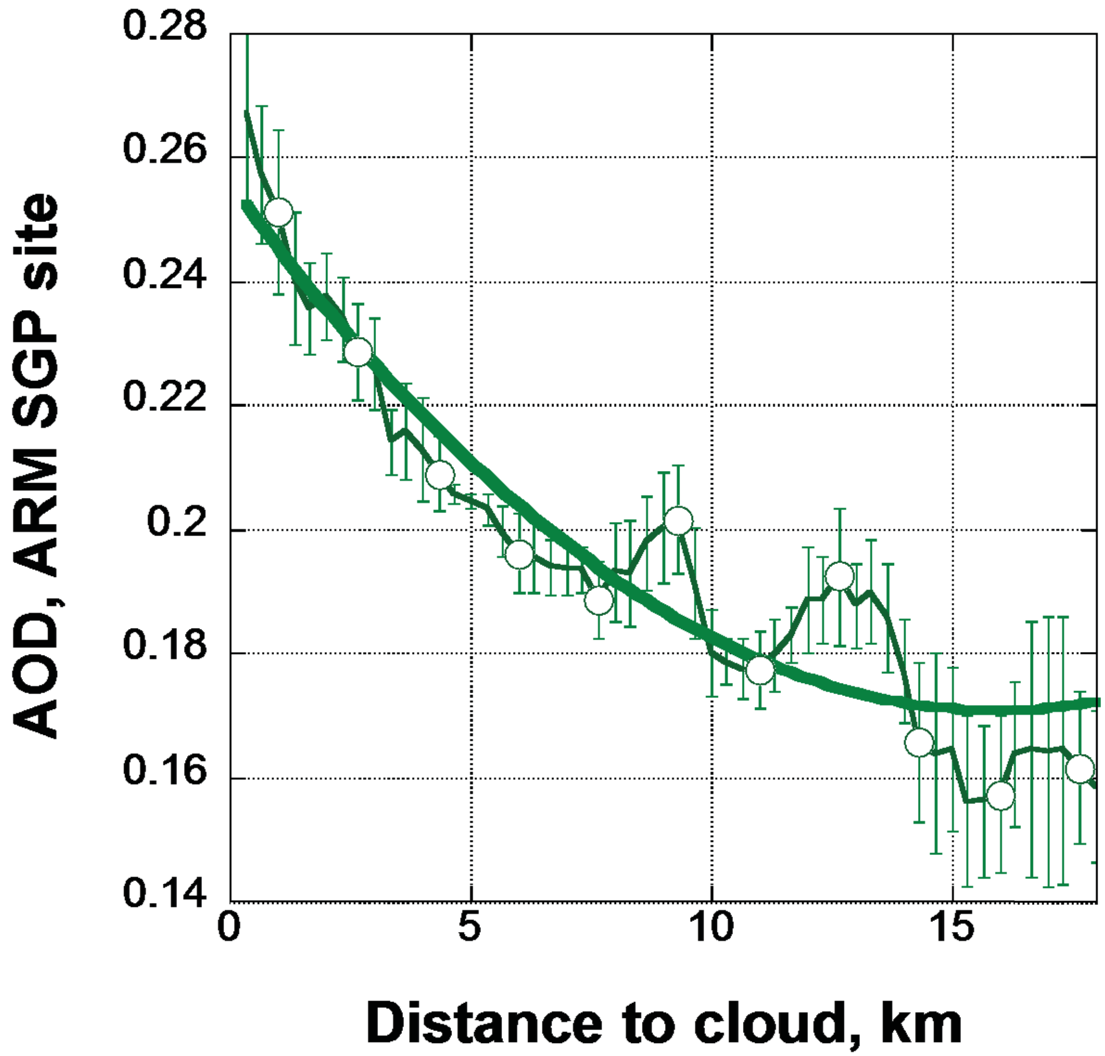
Ilorin
Level10: 1757, 1510, 938, 861, 632
Level15: 1700, 1251, 556, 381, 203
Level20: 1677, 1233, 550, 381, 203

Moldova
Level10: 1079, 814, 446, 413, 374
Level15: 906, 683, 347, 264, 175
Level20: 882, 639, 345, 263, 175

12 other AERONET stations around the globe: AE (440-870 nm)

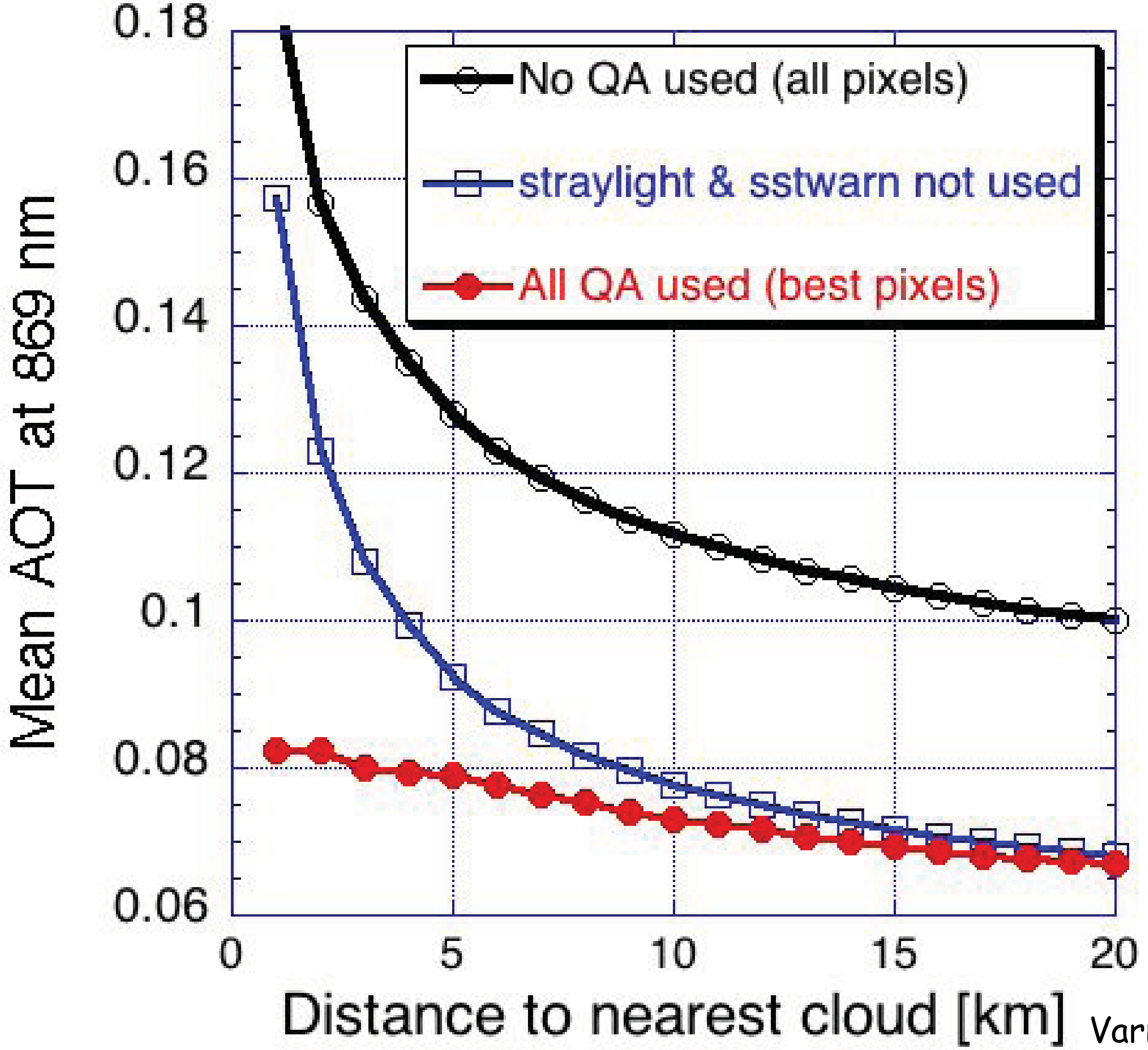


CALIPSO AOD over the ARM SGP site



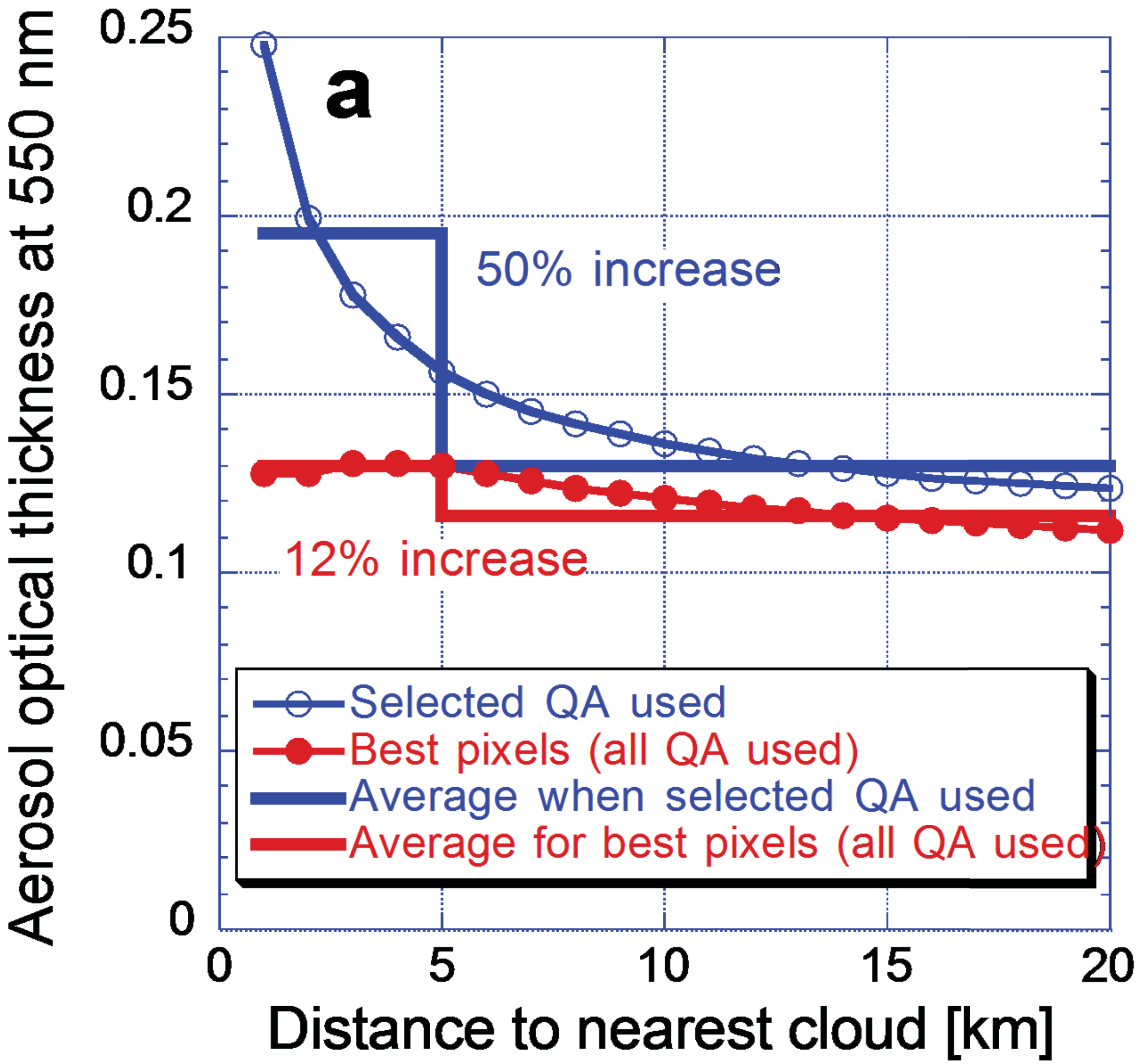
5 years (2007-2011) over a 3° by 3° area around ARM SGP site

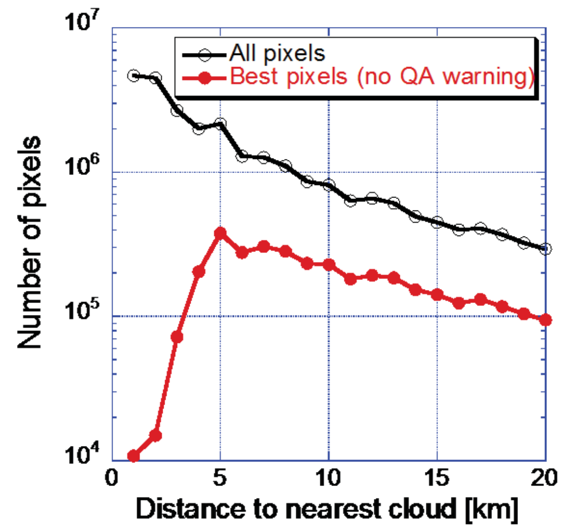
MODIS Ocean Color Product: AOT @ 869 nm



Varnai and Marshak, 2014

MODIS Ocean AOD @ 550 nm



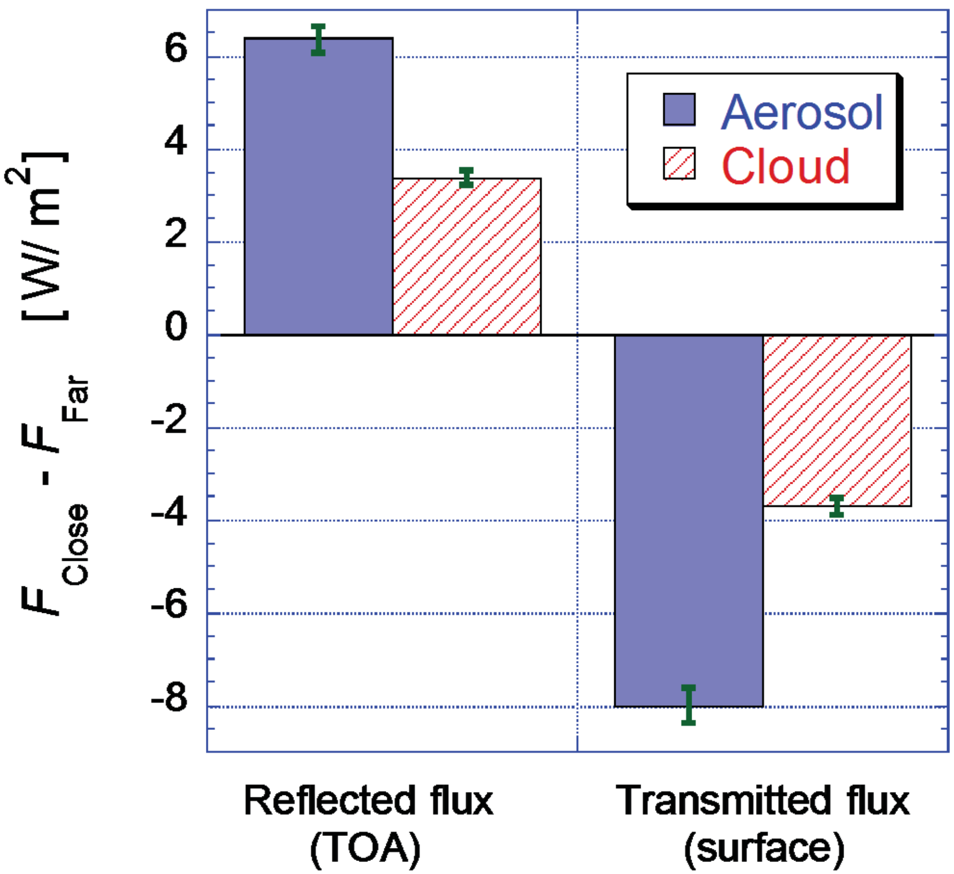


excluding aerosols data near clouds will dramatically reduce the database

Chand et al. (2012) found a 25% enhancement in AOT between CF 0.1-0.2 and CF 0.8-0.9 which was *"consistent with aerosol hygroscopic growth in the humid environment surrounding clouds."*

Impact of AOD differences on direct RF

Varnai and Marshak, 2014



Solid blue and red striped bars show the impact for two interpretations of the difference between AOD *close* and *far* from clouds: all near clouds OD changes are attributed to aerosols (blue) and to undetected clouds (red).

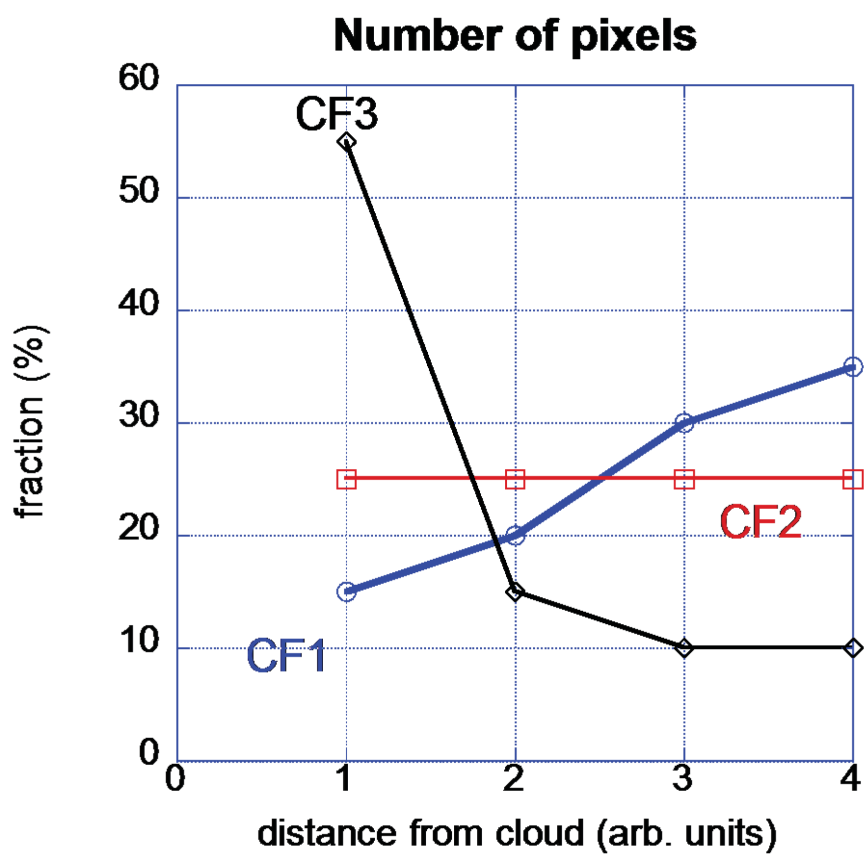
Large-scale meteorology

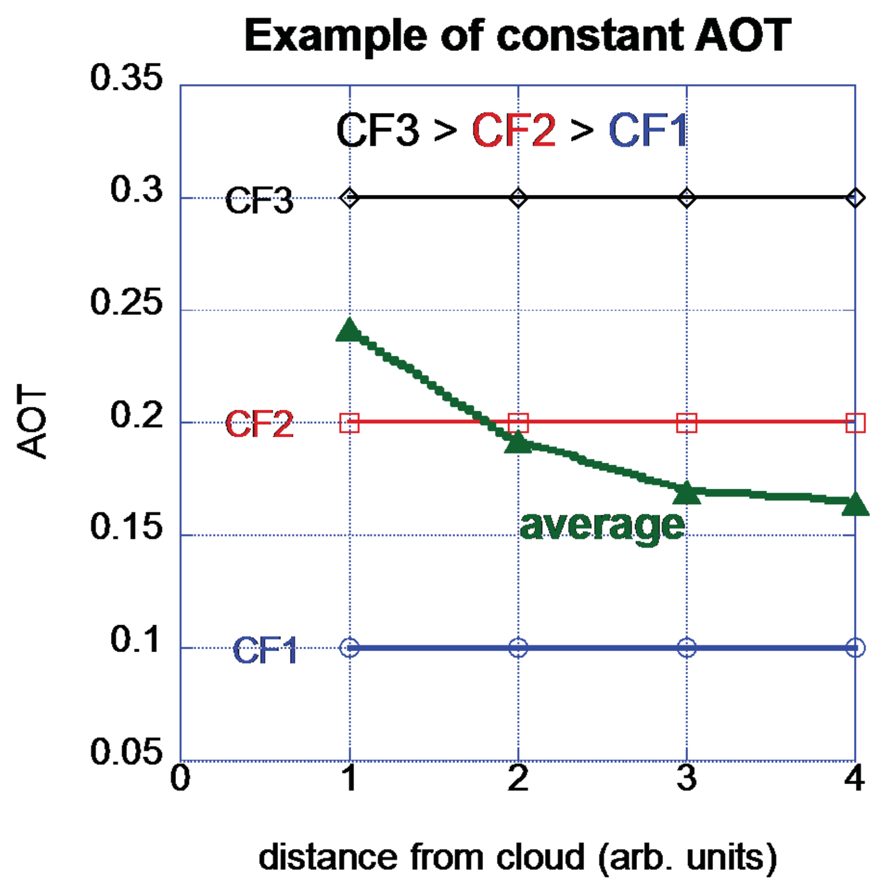
The clear pixels within a few km of clouds are under partly cloudy conditions, while the clear pixels 10-20 km away from clouds are under large-scale high pressure conditions.

The weather patterns and circulations for these two cases can be very different and the AOT and size can be different.

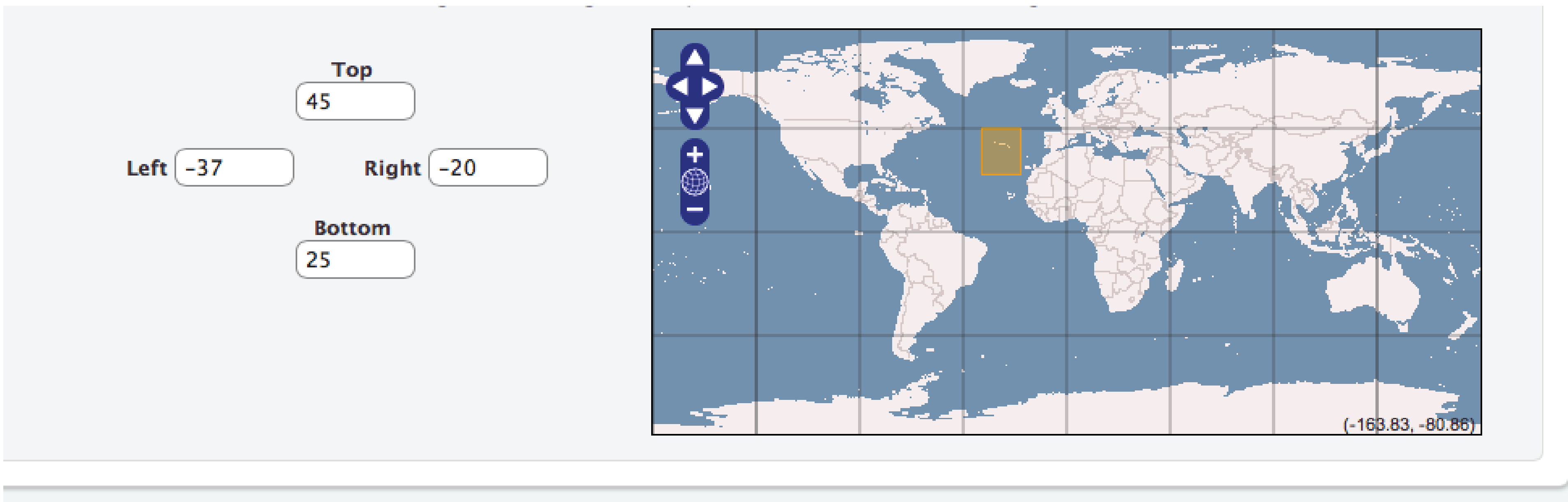
Relative humidity under these two cases is also different: higher under partly cloudy conditions than under large-scale clear conditions.

What's about 'apples' and 'oranges'?

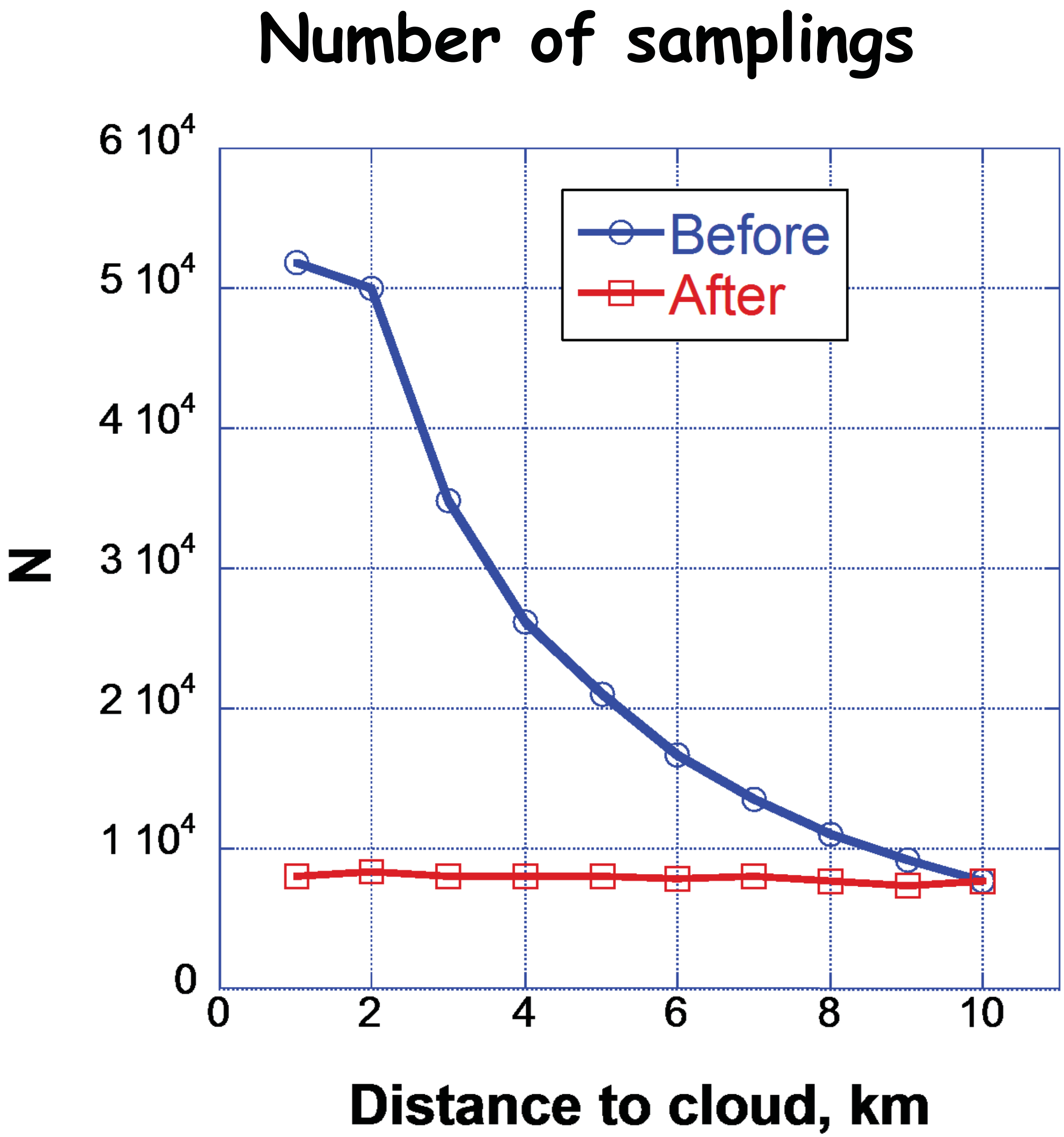




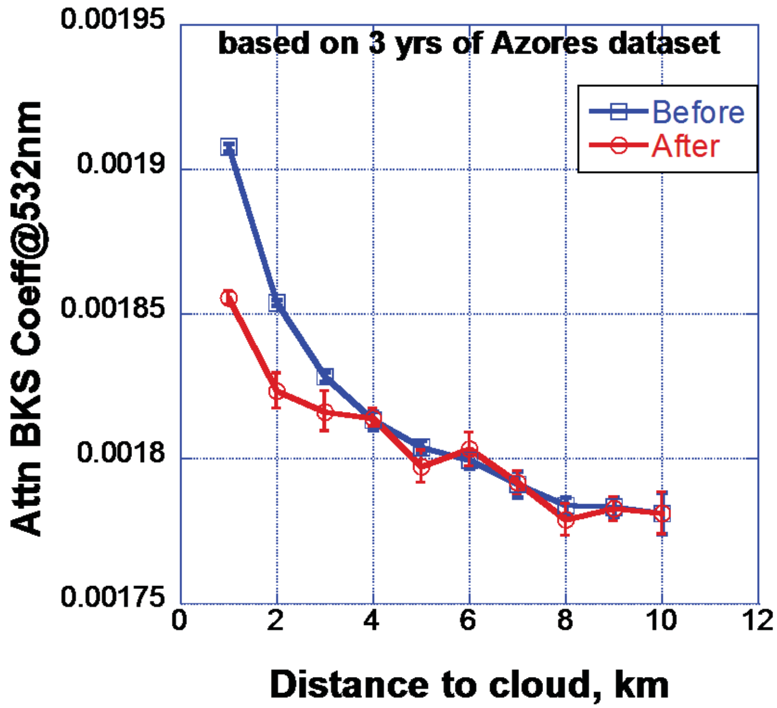
CALIPSO

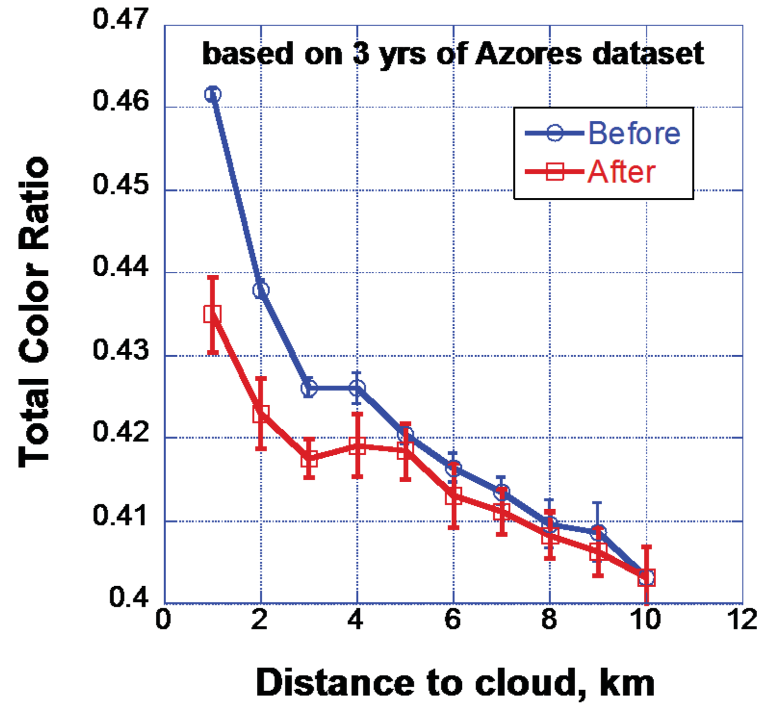


Three year-long observations: 2006.6.21-2009.6.21

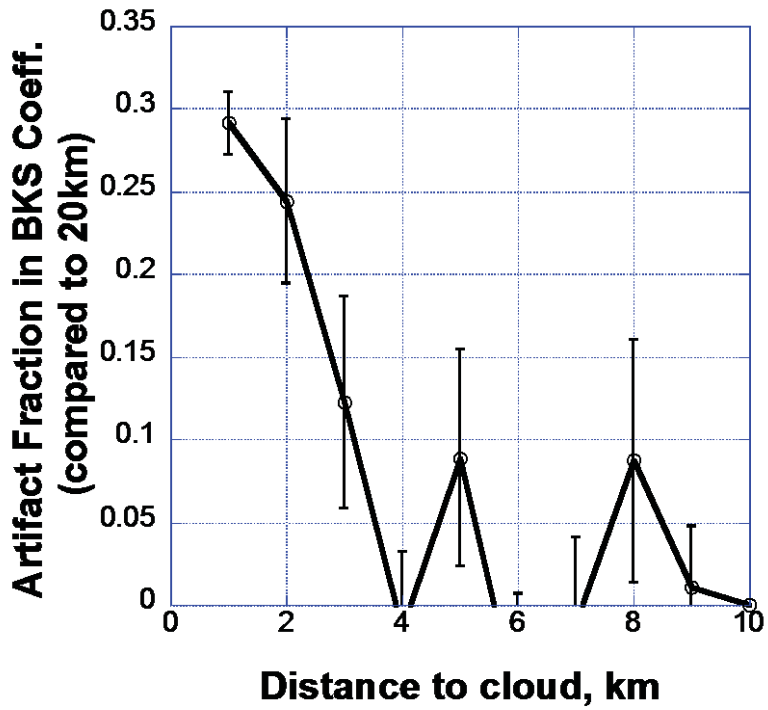

Number of samplings
N
6 10^4
5 10^4
4 10^4
3 10^4
2 10^4
1 10^4
0
0
2
4
6
8
10
Distance to cloud, km
Before
After

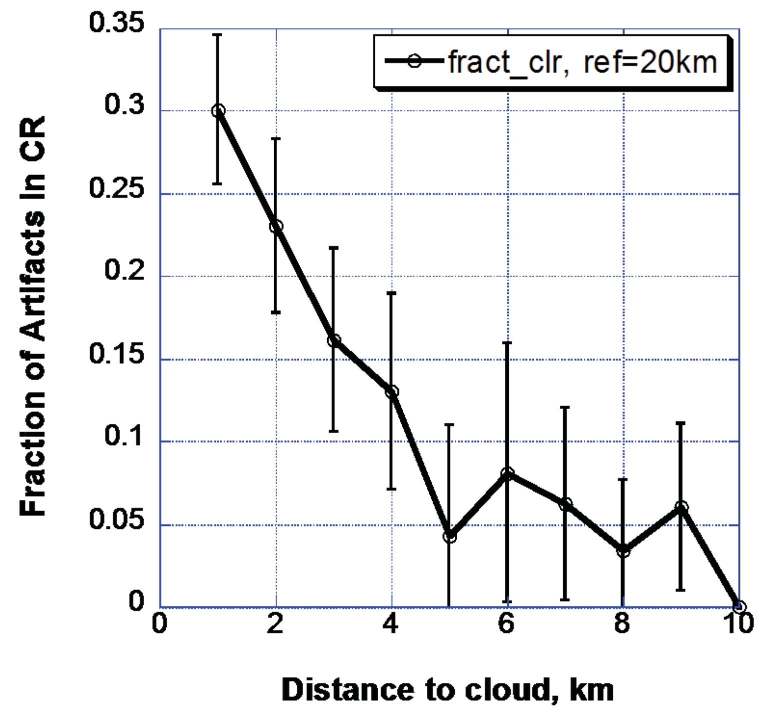
Backscatter and Color Ratio





Fraction of Artifacts





25%-30% is due to sampling bias

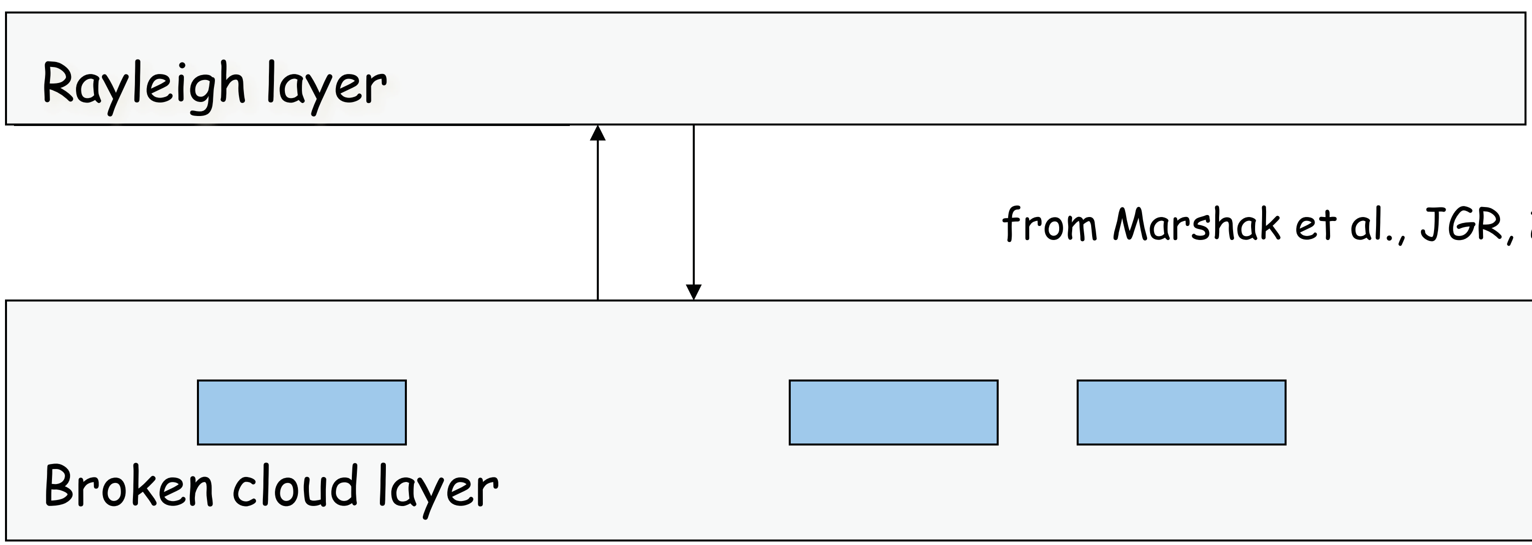
Thank you!

I can show you some slides on the model we use to mitigate the 3D radiative effect of clouds, if TIME permits

How to account for the 3D cloud effect on aerosols?

The *enhancement* is defined as the diff. between the two radiances:

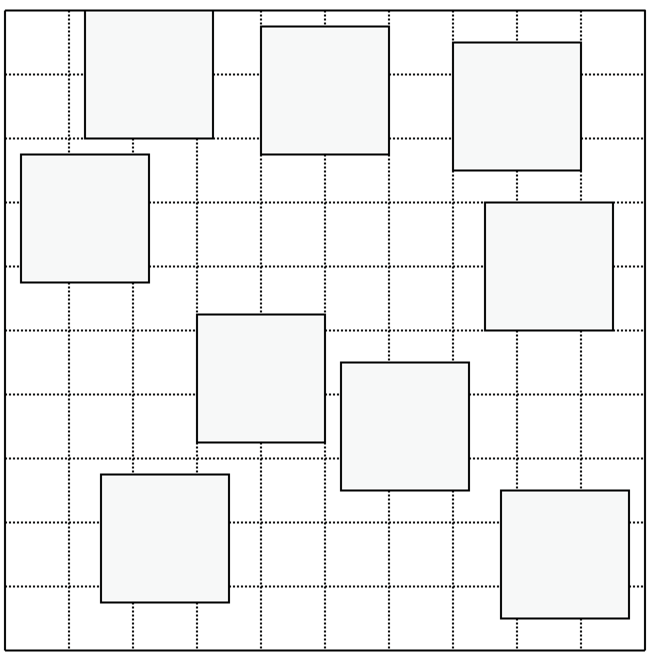
• one is reflected from a broken cloud field with the scattering Rayleigh layer above it
• and one is reflected from the same broken cloud field but with the Rayleigh layer having extinction but no scattering



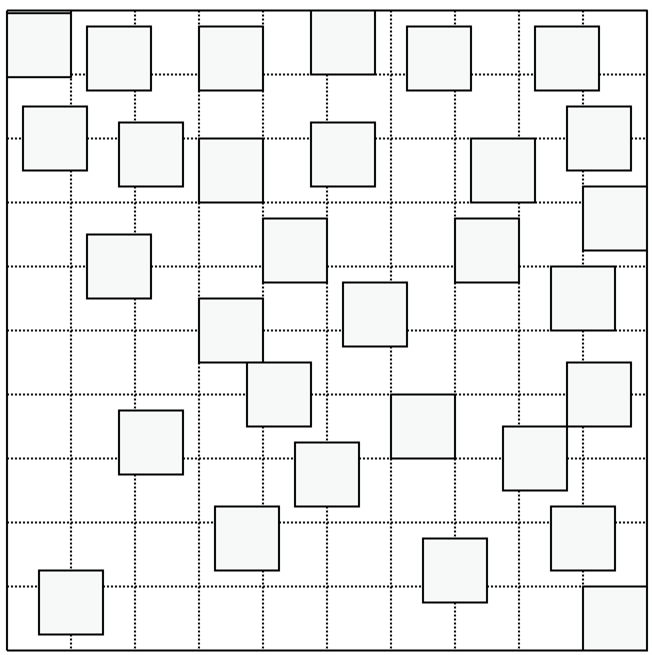
from Marshak et al., JGR, 2008

Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by
- average optical depth
- cloud fraction, A_c
- aspect ratio, AR = hor./vert.



AR = 2

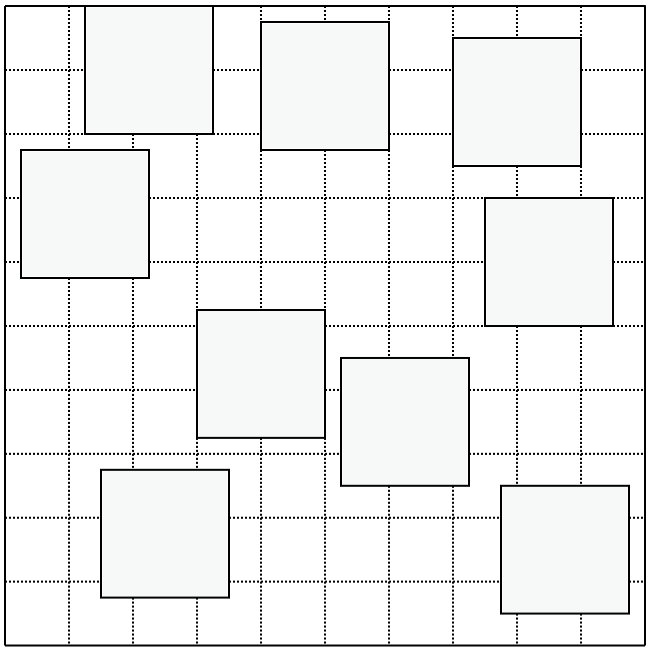


AR = 1

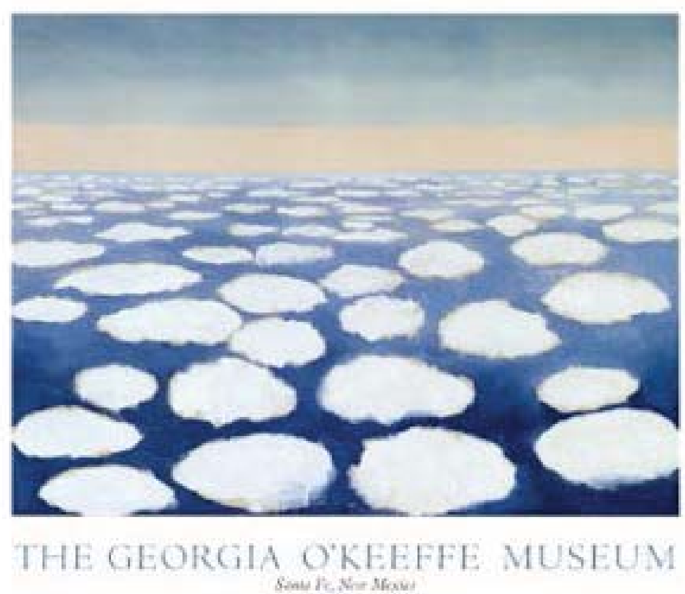
$A_c = 0.3$

Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by
- average optical depth
- cloud fraction, A_c
- aspect ratio, AR = hor./vert.

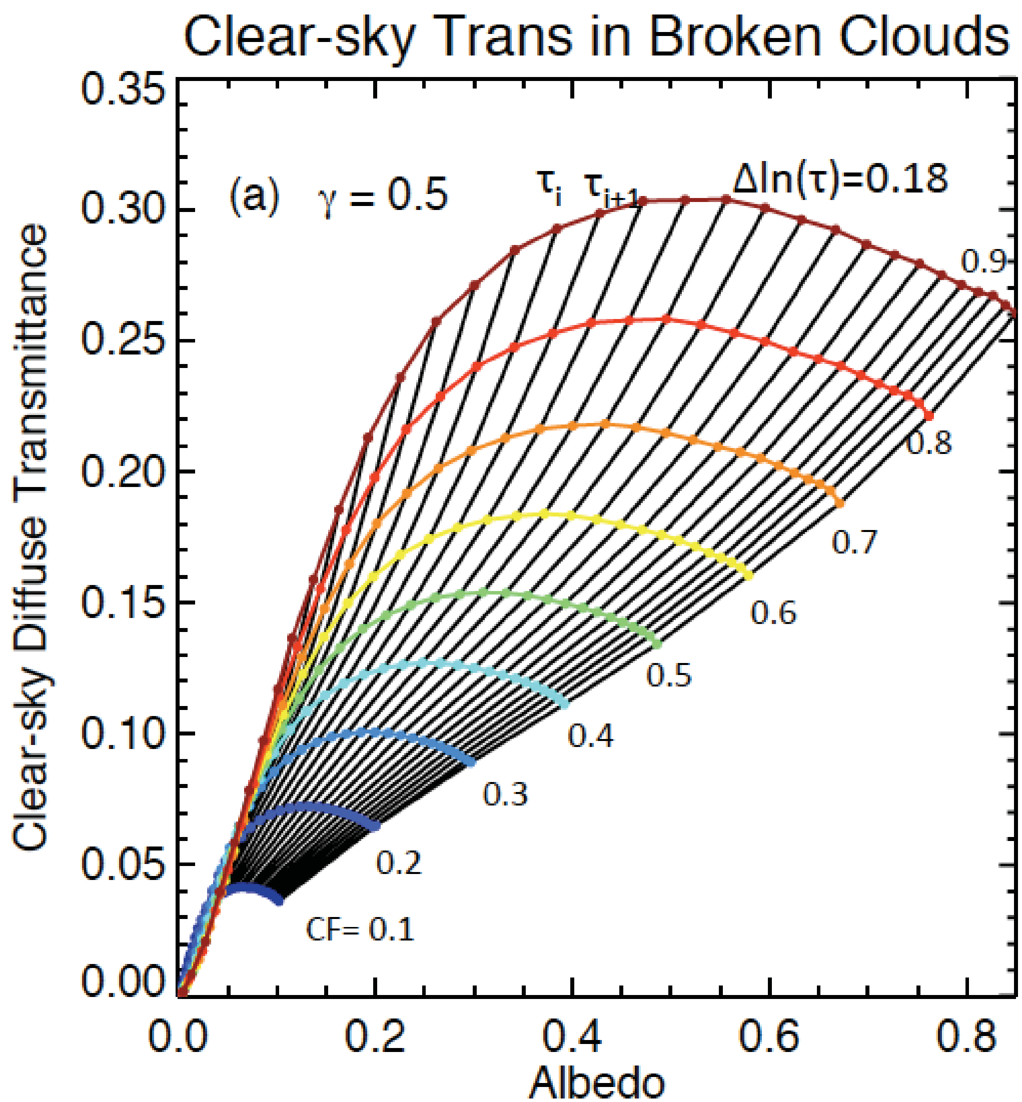


AR = 2



$A_c = 0.3$

Correction for Cloud-Surface Interaction



Application to MODIS granule

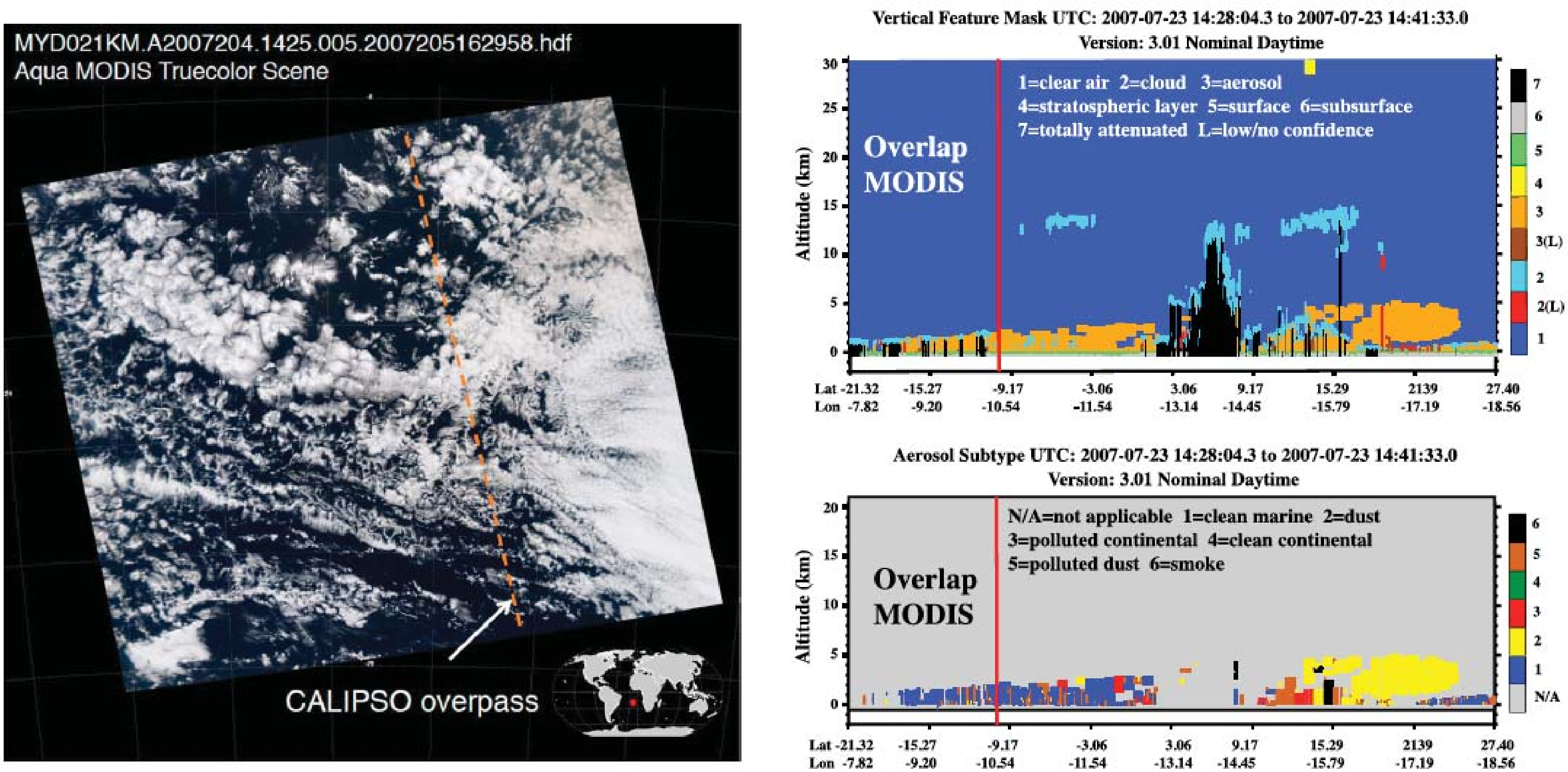
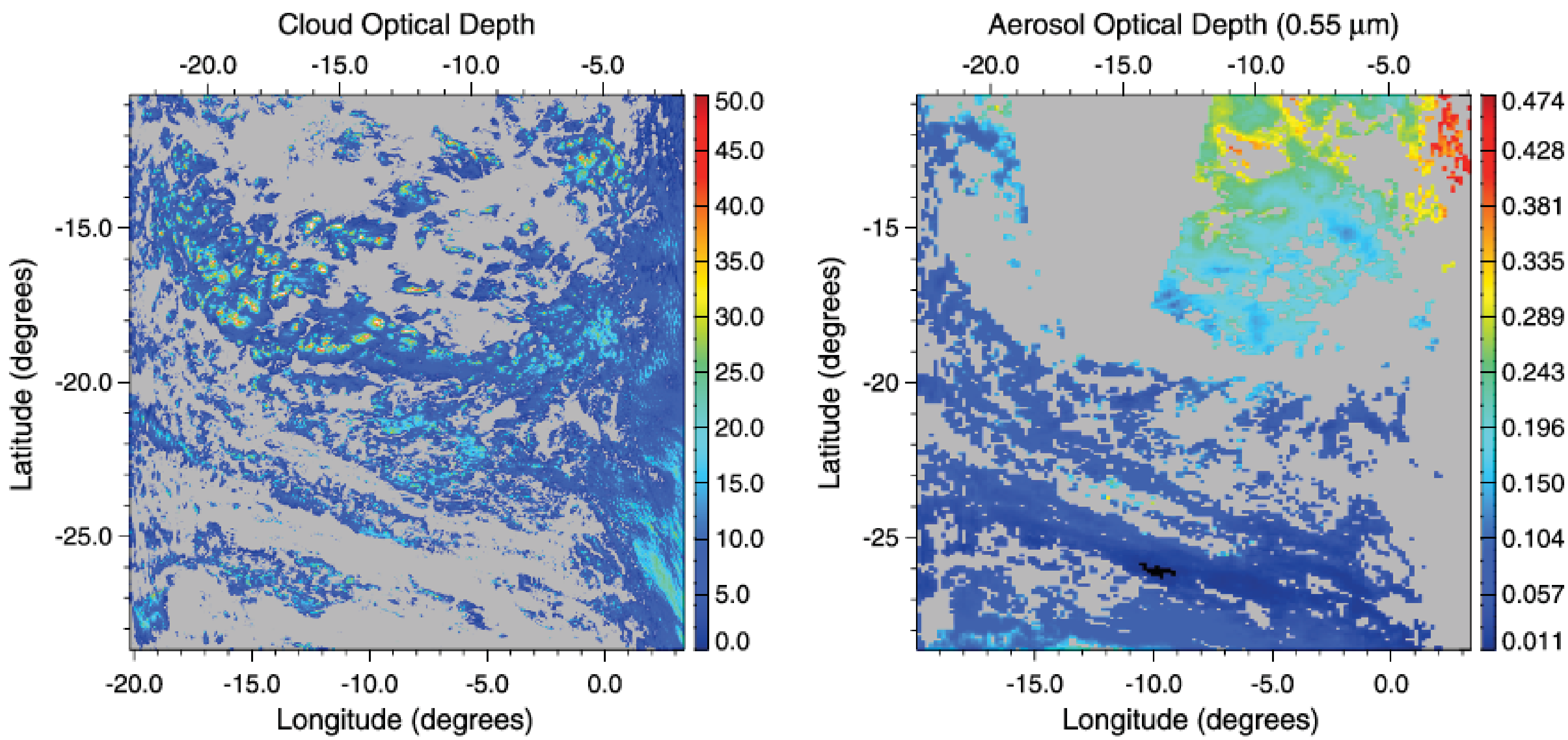


Figure 4. (left) MODIS granule acquired from Aqua MODIS on 23 July 2007 1425 UTC with CALIPSO overpass indicated. (right) CALIPSO observations show that clouds and aerosols are trapped in the boundary layer below 2 km. Regions overlapped with MODIS are indicated.

Wen et al., 2013

Application to MODIS granule



Wen et al., 2013

Application to MODIS granule

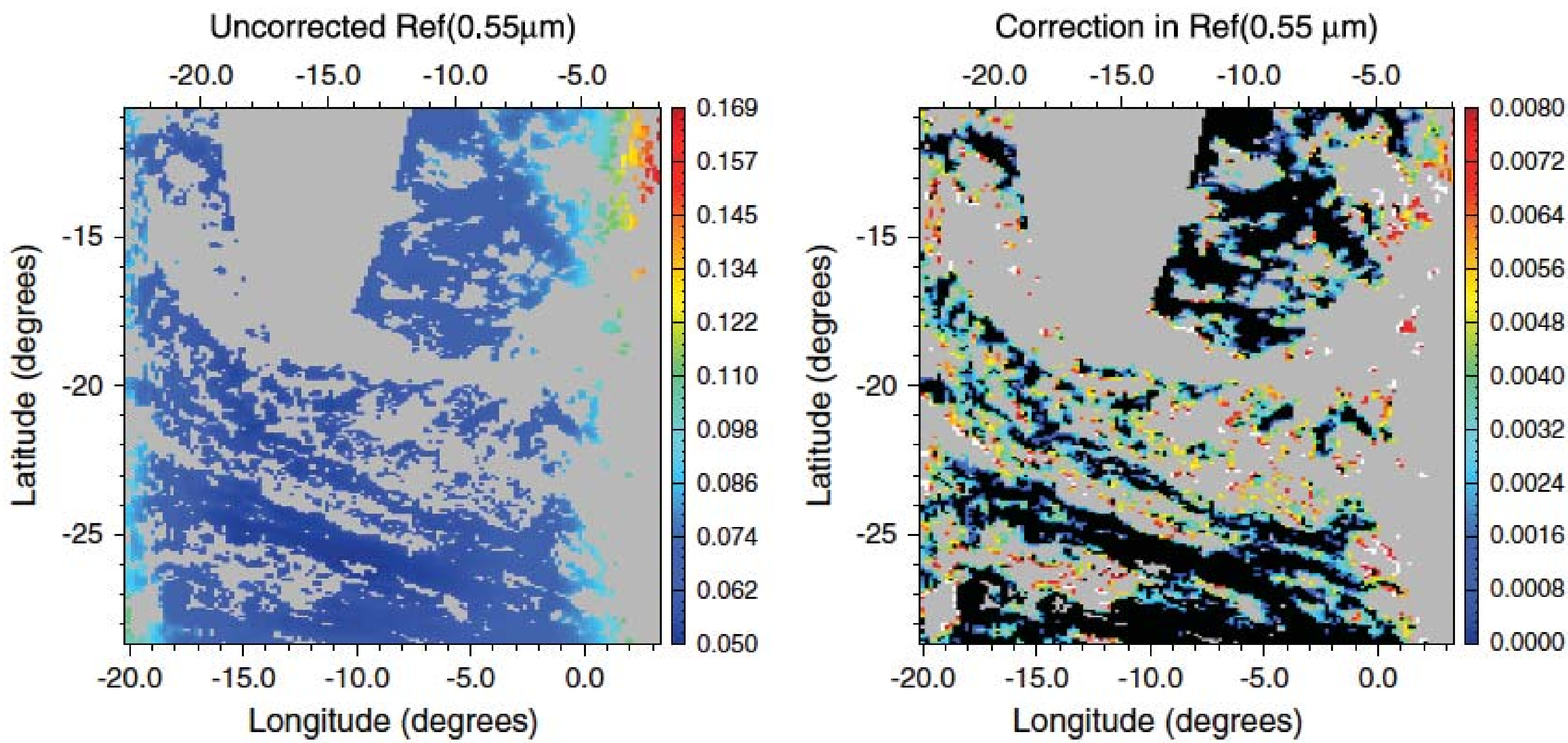


Figure 7. (left) Uncorrected MODIS reflectance at 0.55 μm. (right) The correction of reflectance. The average reflectance correction is 0.004 with a standard deviation of 0.002. Pixels (~2.4%) with reflectance correction values above the upper bound of the color bar (0.008) up to 0.016 are indicated in white.

Wen et al., 2013

Take home message

- About half of all clear sky pixels are within 5 km of a low cloud;

- Aerosol properties (thus radiative forcing) in these area might be significantly different from those far from clouds;

- We cannot separate aerosol radiative forcing of climate into "direct" and "indirect" components;

- Remote sensing retrievals near clouds is challenging but excluding aerosols near clouds dramatically reduces the data volume and underestimates the forcing, while including them may overestimate it due to undetected cloud droplets and other artifacts;

- We must directly confront the transition zone to solve the aerosol-climate problem!

Acknowledgments:
- NASA Radiation Sciences Program;
- NASA CALIPSO/CloudSat Project;
- DoE ASR Program.

Thank you!

What's the transition zone (TZ)

The TZ between cloudy and clear air is a region of strong aerosol-cloud interactions where aerosol CCN humidify and swell when approaching the cloud, while cloud drops evaporate and shrink when moving away from the cloud.

The TZ tends to be contaminated by 'weak cloud elements', such as cloud fragments sheared off from adjacent clouds.
More precisely (Koren et al., 2009), the TZ consists of fast-changing particle clumps:
(1) aerosols at various stages of uptake of water vapor;
(2) cloud fragments sheared off from neighboring clouds;
(3) incipient clouds that are forming but are not yet stable entities;
(4) hesitant clouds—pockets of near-saturation humidity.

The TZ is difficult to study with current aircraft and with most surface remote sensors because they just don't have the time and/or spatial resolution to do so.